The 88-Inch Cyclotron Vacuum Upgrade

A.S. Ladran, Y. Minamihara, D. Leitner

Lawrence Berkeley National Laboratory
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Abstract

The document summarizes the FY2003 LDRD project “Concepts for a Premier Stable Beam Facility for Low Energy Nuclear Physics”. The effort was focused on the development of a technical plan to substantially upgrade the 88-Inch cyclotron vacuum system. It would greatly expand the capabilities of the accelerator especially in the low energy range and overall increase the ion beam intensity for heavy ions.

It was concluded in this study that it is feasible to disassemble, upgrade and reassemble the 88-Inch cyclotron in a 2.5-year upgrade project. A new vacuum chamber design solution was developed, in which the vacuum chamber plates are welded to the pole pieces with a structural and a vacuum weld. The document includes a detailed cost estimate and schedule for the 2.5-year upgrade project was derived.

The estimated total project costs are 8M$ in FY03 US$, which also includes 2M$ for a mandatory seismic upgrade. These costs are fully burdened and include 20% contingency. It might be feasible to compress this schedule to less than two years, but this will require further optimization of the construction schedule and some options for this are discussed in the report. For example, the schedule was based on a staffing profile of 11 persons and could be accelerated with additional personnel. The estimated project cost (8M$) is small in comparison to the estimated replacement value for the facility of 150 M$ and the scheduled time is significantly shorter than the time that would be required to construct a new facility.

These results were accomplished in a stepwise approach.
First, we have derived a detail ProE 3D CAD model of the Cyclotron from the original prints filed on microfilm or ink drawings, including all documented and undocumented upgrades and changes. The effort was focused on the components critical for the proposed vacuum upgrade. Overall, 127 drawing were drafted in ProE for this project. In addition, the modeling focused on the documentation of all iron parts and the electromagnetic coils. This information will be essential during the upgrade to model the magnetic field. To maintain the performance of the cyclotron, it is critical to preserve the magnetic field configuration as closely as possible. Therefore, the magnetic modeling will be an important tool during the construction phase and during the re-commissioning phase. The 3D model proved to be very useful for this study and was extensively utilized. Initially the model was used to understand the original design and construction of the 88-Inch Cyclotron. It also helped to establish a procedure and timeline to disassemble and reassemble the cyclotron. In addition, the ANSYS models for the finite element analyses (FEA) were extracted from these ProE drawings

As the next step the finite element analyses with ANSYS was conducted to understand the cause of the vacuum dependence on the magnetic field in the cyclotron. The magnetic and vacuum loads on the seal region as well as the Dee tank and resonator tank were modeled with finite element analysis. The results from the FEA were verified with actual measurements of displacements of the magnetic poles. They conclusively explain the observed correlation between the magnetic field and the vacuum and establish the displacement of the magnetic iron poles due to magnetic force as the cause of vacuum leak in the Dee tank.

Based on the results of the FEA study, new vacuum seal concepts were developed and designed. The new design replaces the original (leaking) metal seal with a welded joint. Due to the strong forces, a very careful design of this weldment is necessary. The proposed solution consists of a combination of a vacuum weld and a structural weld.

In addition, the new design replaces the remaining wire and corner seals of the Dee tank with one continuous seal, which will reduce the complexity of the assembly and will further enhance the vacuum performance. Finally, a new vacuum-pumping scheme was developed, that replaces the existing diffusion pumps with a turbo and cryo pump combination. The combination of these enhancements will establish an operating pressure of the accelerator in the high 10^{-8} Torr, which is more than a magnitude better than the currently achievable vacuum pressure.

Chapter 1

The 88-Inch Cyclotron

1.1 Motivation

The goal of the study is to initiate and develop the technical plan to substantially upgrade the 88-Inch Cyclotron accelerator. A key element is to find possibilities to enhance the capabilities of the accelerator in respect to the maximum and minimum final energy as well as the ion beam intensities to reach a wider user base.

To be successful in establishing Berkeley as a key facility for nuclear and applied research, we must begin immediately to position the 88-Inch Cyclotron for this role. Several strong programs are established at the 88-Inch Cyclotron to support this role: The ongoing development of advanced ECR (Electron Cyclotron Resonance) sources ensures leadership in a critical supporting technology. LBNL's close connection to the UC campus, its strong established research programs in nuclear structure and reactions, heavy element chemistry, and weak interactions, as well as advanced instrumentation development such has Gamma Ray Energy Tracking Array (GRETINA) keep the low energy nuclear physics vital in Berkeley.

In addition, the strong national user community for heavy ion radiation effect testing has identified the 88-Inch Cyclotron accelerator as a key facility for this research. Currently, this community is trying to establish a long-term program at the 88-inch Cyclotron for radiation effect testing of electronic equipment, destine for space applications. This momentum opens up new opportunities for the 88-Inch Cyclotron to reposition itself nationally with a new mission.

With the LDRD funds, we have explored the feasibility and cost effectiveness of a major reconstruction of the 88-Inch Cyclotron. A detail engineering analyses resulting in a preliminary design, schedule and cost estimate was conducted. A detail document was prepared which can be used as a basis to develop a longer term vision for the future of the facility at LBNL.

1.2 A Brief Description of the 88-Inch Cyclotron Accelerator

The 88-Inch Cyclotron is a sector-focused cyclotron fed by two high-charge-state Electron Cyclotron Resonance (ECR) ion sources, the double-frequency (14 GHz and 10 GHz) driven AECR-U and the 6.4 GHz driven LBL ECR ion source. A third ECR injector ion source, the superconducting source VENUS is currently under commissioning. Fig. 1.1 shows a schematic layout of the 88-Inch Cyclotron accelerator facility with the three ECR ion source injectors.

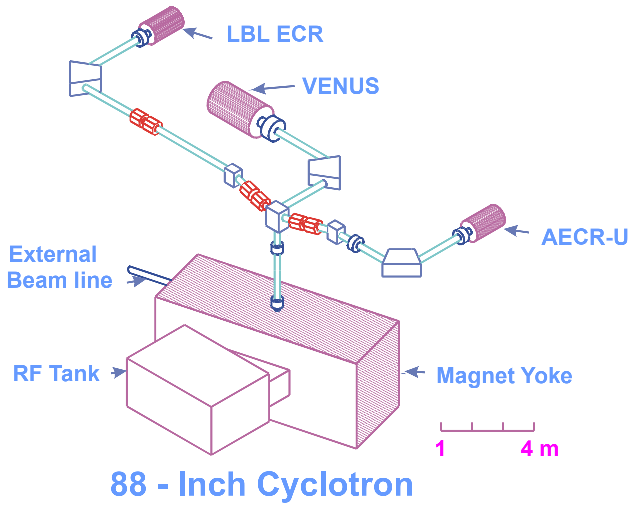

Fig. 1.1 Schematic layout of the 88-Inch Cyclotron accelerator facility

The 88-Inch Cyclotron is nominally a K140 cyclotron. The RF frequency can be varied from 5.5 MHz to 16.2 MHz and both first and third harmonic beams are routinely accelerated. Minimum and maximum energies for the first harmonic and for the third harmonic acceleration are 6.1 MeV and 55MeV/nucleon and 0.7 to 6 MeV/nucleon, respectively.

The factor K can be described as the energy constant of a cyclotron and is connected with the final energy/ nucleon over the equation

$$\frac{E}{A} = \left(\frac{Q}{A}\right)^2 \cdot K \, , \tag{1.1}$$

where E/A is the energy/nucleon, Q is the ion charge and K is the bending limit of the cyclotron magnet. The factor K contains the magnetic field and the extraction radius of the cyclotron and is facility specific. The maximum K of the 88-Inch is 160, but it is usually operated at 130 or lower.

The K factor determines the maximum final energy. It can be easily seen from equation 1.1, that the final energy of a given ion can be increased by injecting higher charge states into the cyclotron accelerator. Therefore, ECR ion sources, which can produce high intensities of high charge state ions, are the ideal injector sources for cyclotrons. Therefore, these ion sources have been extensively developed at the 88-Inch Cyclotron.

Figure 1.2 shows the operational diagram of the 88-Inch cyclotron. The diagram graphs the dependence of the final energy to the mass to charge ratio and the magnetic field. The y-axis graphs the magnetic field, the lower x axis shows the particle revolution frequency, and the upper x axis shows the energy per nucleon that can be reached. The straight lines graph the possible energy range for a given mass to charge ratio.

For protons, the upper energy limit is determined by the maximum Dee frequency of 16.2 MHz, for heavy ions the upper energy limit is determined by the maximum magnetic field and injected charge state.

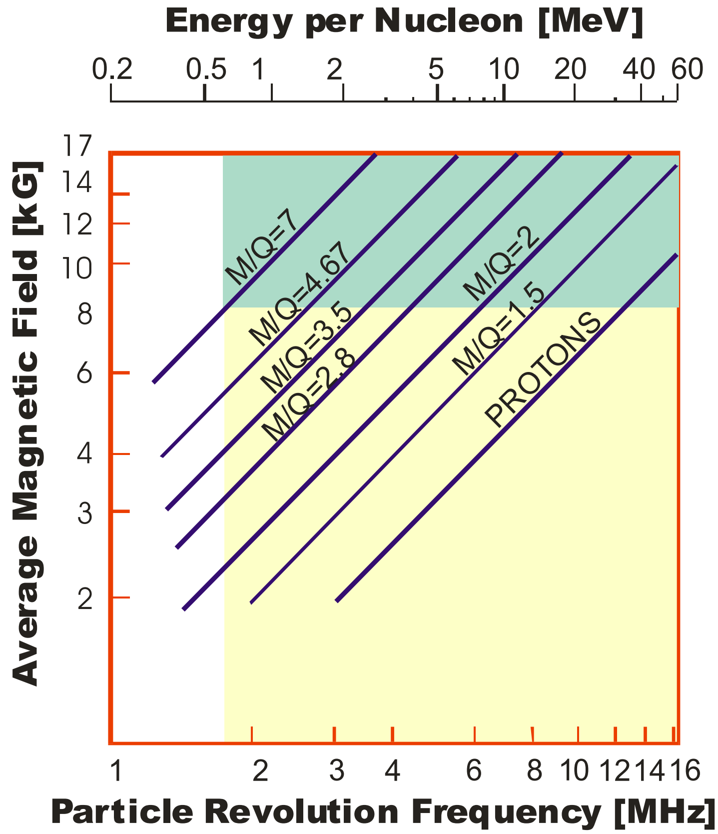

Figure 1.2 The 88-Inch cyclotron resonance chart. Operating lines for various particles show magnetic field, frequency and energy per nucleon. The maximum particle energy is limited by the maximum magnetic field, except for 3He2+ and protons, where it is limited by the maximum Dee frequency.

Figure 1.2 also demonstrates the great energy flexibility the cyclotron accelerator can offer, if it is operated over the full range of the magnetic field. The main limitation for the accelerator has been a vacuum leak that develops at magnetic fields in the cyclotron below 800 kGauss. This leak has existed since the startup in 1961. The main vacuum seals between the iron pole pieces and the vacuum tank plate have been identified as the primary cause. Attempts have been made over the years to plug this leak by accessing the seals via the pump out ports (see chapter 2 and 3), but those attempts have not been successful. Therefore, the typical operational range for the cyclotron has been restricted to the green shaded area in Fig.1.2. The purpose of this study is to find an engineering solution to redesign the vacuum seals of the Dee tank to achieve a consistent vacuum pressure over the full magnetic field range. This would greatly expand the capabilities of the accelerator especially in the low energy range and would make it possible to extract several particle microamperes of heavy ions at energies down to .7 MeV per nucleon. This low energy range would be particular interesting for astrophysics cross section measurements.

In addition, it would also increase the intensity of heavy ions over the whole range, which would benefit the heavy element chemistry and physics program at the 88-Inch cyclotron. The vacuum upgrade would be particular important for the heaviest ions, since the charge exchange cross section between heavy ions and the residual gas in the cyclotron Dee tank increases with charge state and ion mass. Therefore, the cyclotron vacuum upgrade would be especially effective for the heaviest, high charge state ions such as U^{50+} or Xe^{44+}.

Finally, a vacuum upgrade would also allow more flexibility in choosing the most efficient charge state for acceleration. This would increase the efficiency of the ECR ion sources, lower material costs for rare isotope beams, and decrease power costs.

1.3 3D CAD Model of Cyclotron

The ProE CAD drawings for the Cyclotron were developed from the original detail drawings filed on microfilm or ink drawings. They include production and assembly drawings. Not all the original drawings were updated over the years. The current ProE CAD models include all upgrades and changes. Included in the appendix of this document is a spreadsheet associating the drawings by drawing number with the appropriate CAD files. As an example, figure 1.3 shows the main assembly of the cyclotron accelerator and a detail drawing of the center region, in which the beam is inflected by a gridded mirror inflector from the axial injection line into the cyclotron and accelerated during the first turns.

Not all components of the 88-Inch Cyclotron were modeled in detail. Instead, the effort was focused on the areas most important for the proposed vacuum upgrade. Table 1 summarizes the components, which were modeled in detail. 127 drawing were drafted in ProE for this project (see appendix). In addition, the modeling focused on the documentation of all iron parts and the electromagnetic coils. This information can be used during the upgrade to model the magnetic field in TOSCA. It will be critical for the upgrade project to preserve the magnetic field configuration of the cyclotron as closely as possible and therefore magnetic modeling will be an essential tool during the construction and commissioning phase after the upgrade.

The 3D model was extensively used for this study. Initially the model was used to understand the original design and construction of the 88-Inch Cyclotron. The model was used to establish a procedure to disassemble and reassemble the cyclotron. In addition, the finite element analyses models developed in ANSYS were extracted from the ProE models. Finally, the model was used to design and engineer the Dee tank vacuum chamber.

This new set of drawings makes it easier to implement further upgrades in the near future and is very useful for the accelerator maintenance. It would be advisable to continue this effort to the remaining hardware components such as the RF tank.

Table 1.1 List of hardware components modeled in ProE in detail, major subassemblies are shaded in different colors.

Magnet			
Yoke	Poles	Main Coil	Trim Coil
	Magnet Pole Tips		
	Midhill		
	Outer Hill		
	Inner Hill		
Dee Tank			
Main Assembly	Main Plate - Upper	North Cover Plate	
	Main Plate - Lower	East Cover Plate	
		South Cover Plate	
Dee			
Dummy Dee			
Center Region			
Dee Insert	Dummy Dee Insert	Iron plug	
Axial Injection			
Glaser Lens #3	Inflector IV		
Deflector II			
Resonator Tank			
Upgrade Components:			
Welded Dee tank	Tank vacuum seal		

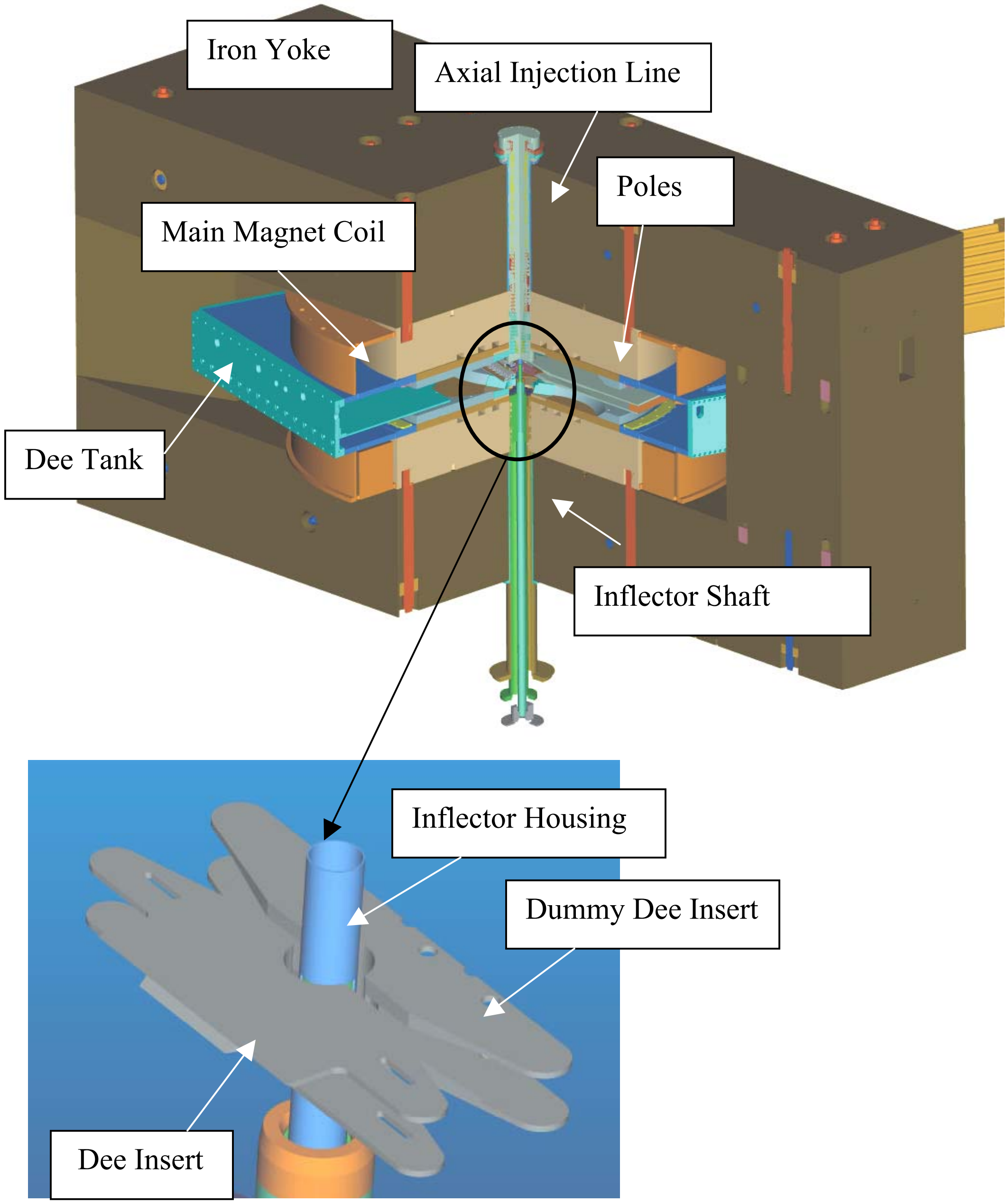

Figure 1.3 The 88 Inch Cyclotron assembly in the ProE CAD model and the center region detail.

Chapter 2

2.1 88–Inch Cyclotron Vacuum System Overview

The current vacuum system of the 88-Inch Cyclotron consists of two diffusion pumps in the RF tank backed by roots blowers, two cryopumps in the cyclotron tank, one cryopump on the Dee insert coffin, and two cryopanels in the cyclotron tank (main north cryopanel and the south port cryopanel). The two diffusion pumps have an approximate pumping capacity of 7000 lps air each, the cryopumps on the cyclotron tank have about 3000 lps air each, and the cryopump on the Dee insert coffin has about 1500 lps air. A pair of 1420 liquid nitrogen cooled helium gas refrigerators cools the two cryopanels to about 15 K. Two 1400 reciprocating helium compressor supplies drive the helium gas refrigerators. A schematic of the cyclotron vacuum system is shown in Fig. 2.1.
The original vacuum seals for the Dee vacuum tank consists of an elaborate system of double wire seals, bolt seals on every bolt and a multi-part corner seal. A more detail description is given in chapter 4. The Rf tank is O-Ring sealed.

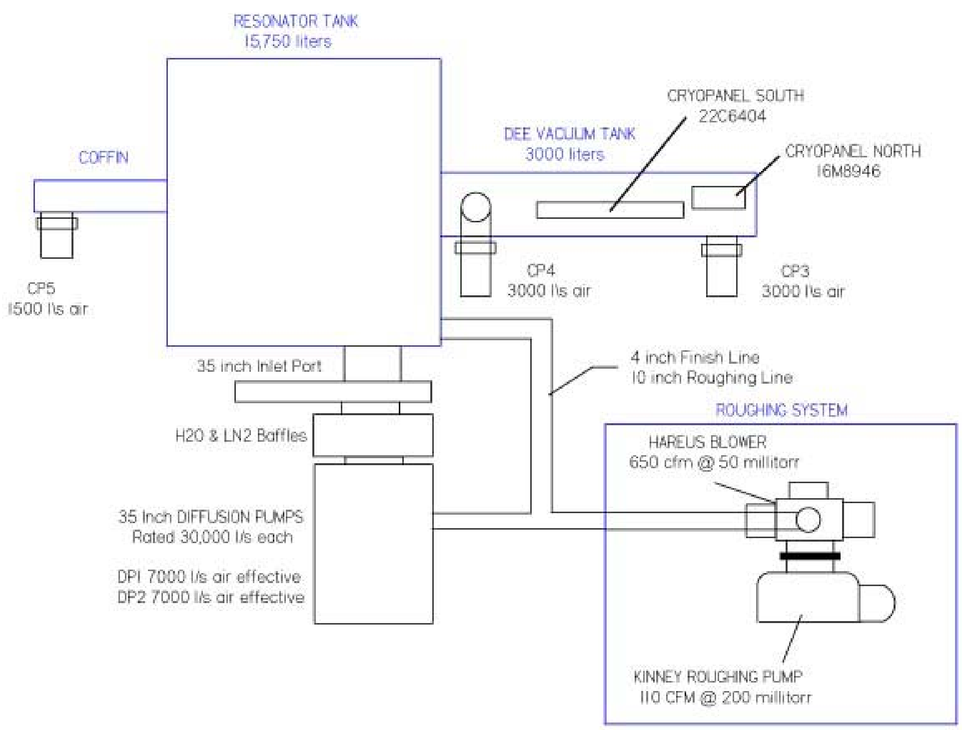

Figure 2.1 Vacuum System Schematic

2.2 Description and Documentation of the Vacuum Pumping System

The present vacuum system is documented in several drawings [i] [ii] [iii] [iv] [v]. Several modifications and improvements have been implemented to the original vacuum system. These changes include

- In 1967 the DP 32 inch Hg diffusion pumps were replaced with DP35 inch oil diffusion pumps. In addition, the water baffles and LN2 traps were upgraded. Although the DP35 pumps have been measured at around 30,000 lps; with the baffles and LN2 system the measured effective pumping speed of the DP system at the resonator tank is reduced to 7000 lps. [vi]

- A cryopanel was installed in 1974 on the NorthEast side of the Dee tank. Another cyropanel was installed in 1994 along the South side of the Dee tank.

- The diffusion pumps DP 3 and DP 4 on the Dee tank were replaced with cryopumps. Diffusion pump DP 3 was replaced with CP3, which is an ASC-Crygenics CP-10 (3000 lps air). Diffusion pump DP4 was replaced by CP4, which is a CRYOTORR 10 (3000 lps air).

- An additional cryopump was added to the coffin DP5, a CTI-Cryogenics Cryo-Torr 8 (1500 lps air)

2.3 Performance of the existing vacuum system

The current best performance of the vacuum system is a pressure in the low 10^{-6} Torr in the RF tank to 10^{-7} Torr at the cryopumps. This relatively modest performance is due to several known vacuum leaks. These vacuum leaks have existed in the 88-Inch cyclotron since the startup in 1961. However, the main vacuum seals between the iron pole pieces and the vacuum tank plate have been identified as the primary cause. As shown in chapter 3, this dependence is caused by a movement of the upper and lower iron yoke under the magnetic forces, which compress the wire seal and temporally improve the air leak. Attempts have been made over the years to plug this leak by accessing the seals via the pump out ports. The ports have been filled with liquid sealants, permatex and even vacuum grease. These "remedies" seem to improve vacuum some, but the only consistent vacuum improvements have been observed when the main magnet coil current exceeds a threshold value. The relationship between magnet and improved vacuum has been consistent even though the steel yoke and poles have been cycled thousands of times under both magnetic and vacuum loads. Figure 2.1 shows the dependence of the vacuum pressure to the main magnet coil current.

2.4 Performance Goal of the proposed vacuum upgrade

The goal of the proposed vacuum upgrade is to improve the vacuum pressure at the Ion Gauges IG6, IG10 to reach the low 10^{-7} to the high 10^{-8} Torr range independently of magnetic field. This would also significantly improve the vacuum in the center region with a target of the high to mid 10^{-7} Torr range. In addition, the changes proposed would also decrease pump down time and reduce maintenance requirements.

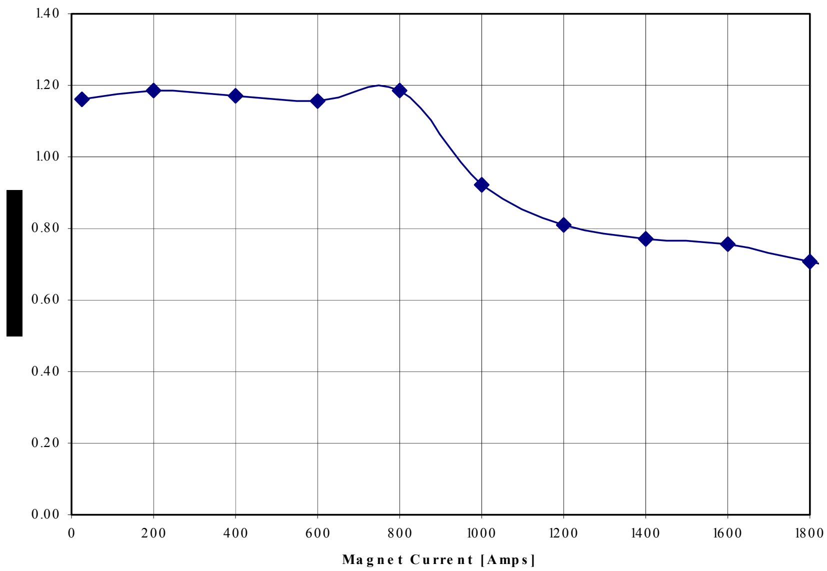

Figure 2.1. Dependence of the vacuum performance of the 88-Inch Cyclotron to the main magnet coil current (cyclotron field). The vacuum starts to improve at currents above 800 Amps.

2.5 The Vacuum Upgrade

The upgrade design will replace the main knife-edge seal with a welded joint (See Fig.2.2). This seal will be replaced with a welded joint between the pole and the Dee tank similar to the design successfully used in the Texas A&M 88-Inch Cyclotron, which does not exhibit the same main coil current dependence for the vacuum.

The new seal design is described in detail in chapter 4. In addition, all the original wire metal seals and the corner seals will be replaced with a continuous elastomer or tin seal (see chapter 7.2)

Furthermore, updates to several other vacuum components at the LBNL 88-Inch Cyclotron should be implemented to further improve the vacuum performance. To achieve the desired vacuum pressures of low 10^{-07} to high 10^{-08} Torr, it will be necessary to replace the existing oil diffusion pumps with a combination of cryogenic and turbo molecular pumps. The existing cryo pumping panels (LN2 and helium) will be kept and the benefit of additional ones should also be considered.

Furthermore, a differential pumping system to separately pump out the trim coil trays can be considered. A similar scheme was originally suggested in a memo sent out in the early 1960s by A. Hartwig.[vii] The trim coil[viii] redesign will have to be closely coupled with the vacuum system.

2.5.1 Summary of Vacuum Upgrades

The following section summarizes the major upgrades proposed for the vacuum system. The names and locations of the vacuum components referred in this item no. 1 of this section are described in LBNL Drawing no. 15D8716A - 88" Cyclotron. The Dee tank upgrade is shown in Chapter 4. Items 4, 5 and 6 are optional and are not explored further in this document.

1. Pumping System (shown in Figure 3-2)
    a. Replace 35-inch Diffusion pumps, water baffle, LN2 baffle with a cluster of 1000-3000 lps cryopumps for water and UHV and 2000 lps turbo pumps to scavenge light gases and shorten the pump down times.
    b. Retain existing roots blower roughing system MP 1,2,3,4,6
    c. Retain house air system MP5
    d. Retain Cryopumps CP 4 (Dee Tank), CP 3 (Extraction), CP 5 (coffin)
    e. Maintain no bake out requirement

2. Dee Tank
    a. Replace knife edge seal with a welded joint (poles and Dee tank plate may not be reusable)
    b. Eliminate the corner seals and replace with o-ring type gasket.
    c. Replace wire seals on tank side wall plates with o-ring seals
    d. Replace wire seals on RF Tank to Dee tank interface with o-ring seals
    e. Eliminate wire seals on all bolts.

3. Welded Pole Seal
    a. Replace knife-edge seal with a welded joint (weld the pole to the Dee tank vacuum plate.

4. Optional - Design a new cryo-panel to add to, or replace existing ones in the Dee vacuum tank.

5. Optional - Measure the leak rate and if necessary redesign the inflector vacuum seal.

6. Optional - Install differentially pumped trim coil tray.[ix] [x]
    a. Replace Copper tray with new closed design to provide differential pumping.[xi] [xii]
    b. Design an o-ring gasket mating surface to Dee tank.
    c. Coordinate with trim coil and valley coil redesign. (1500 hrs for trim coil assembly[xiii])
    d. Design vacuum pump ports on Dee tank. A location should be located on the top and bottom plate that is within trim coil envelope and has headroom for a valve and pump assembly.
    e. Size turbo and cryopumps for trim coil tray volume. (account for virtual leaks and low conductance cross sections).
    f. Design a roughing vacuum system specifically for the coil tray system
    g. Design an interlock system to prevent pressure difference between trim coil tray and Dee tank during pump down and if vacuum is lost.

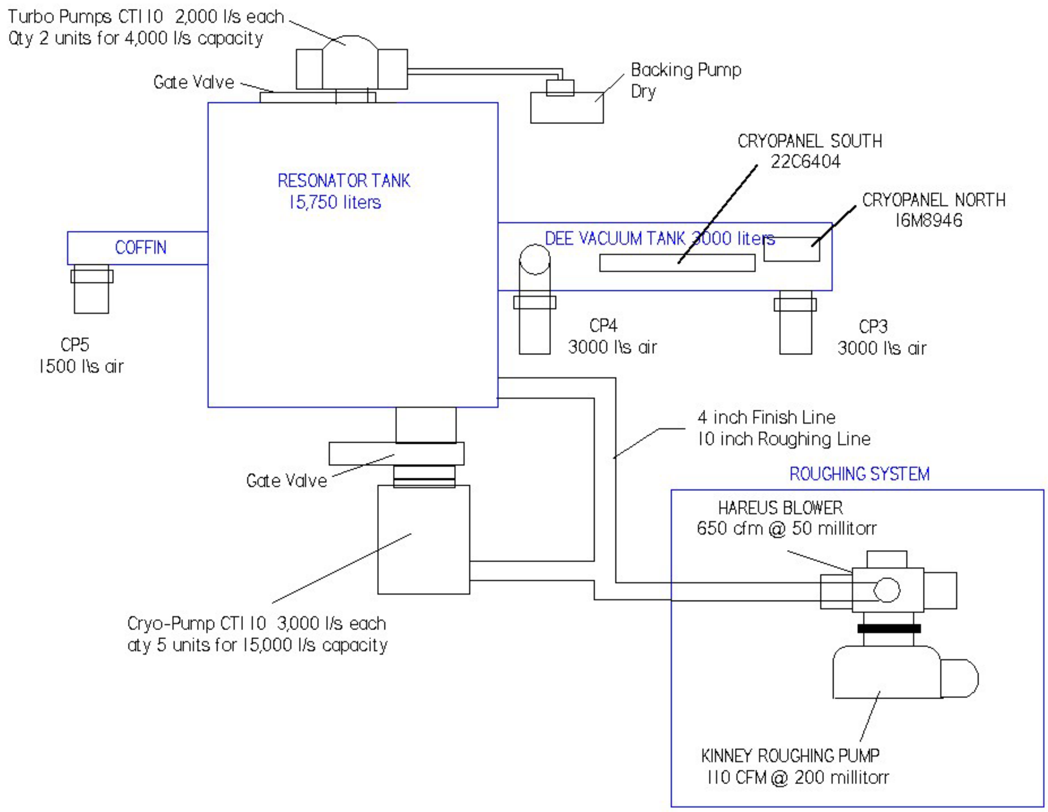

Figure 2.3 Vacuum upgrade – New turbo and cryo-pumping system schematic.
In this is the proposed vacuum layout the two 35 inch diffusion pumps are replaced with a combination of cryopumps and turbo pumps.

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[i] LBNL Dwg.16M8946, 88-inch Cyclotron Cryogenic Pumping System, Panel Assembly, 1974
[ii] LBNL Dwg.22C6404, 88-inch Cyclotron Cryo Pumping, LN Panel Assembly, 1994
[iii] 15D8716A - 88" Cyclotron, Vacuum System, Flow Diagram (Revision II), 1969
[iv] 9C3455B - 88" Cyclotron, Vacuum System, Pump Room Piping Arrangement, 1960
[v] 15C6736 - 88" Cyclotron, Vacuum System – 35" D.P., Cold Trap Assembly, 1967
[vi] Reinath, Finn S., Project: 88-inch Cyclotron Vacuum System, 35-inch Oil Diffusion Pumps (PMC-32B), Title: Trapped and Untrapped Pumping Speeds for Air with D.C. 705 D.P. Oil., LBNL Engineering Note M3915, June 13, 1967 13 pages
[vii] Hartwig Memo, 88" Cyclotron Vacuum System Main Seals Situation to Date and Suggestions for Future Procedure., no date.
[viii] L.R. Glasgow, R.J. Burleigh, Trim-Coil Construction for the Berkeley 88-inch Cyclotron., Nuclear Instruments and Methods 18,19 (1962) 576-581
[ix] Hartwig Memo, 88" Cyclotron Vacuum System Main Seals Situation to Date and Suggestions for Future Procedure., no date.
[x] L.R. Glasgow, R.J. Burleigh, Trim-Coil Construction for the Berkeley 88-inch Cyclotron., Nuclear Instruments and Methods 18,19 (1962) 576-581
[xi] 9B8115 - 88" Cyclotron, Magnet Trimming Coil, Base Assembly, 1960
[xii] 9B8506 - 88" Cyclotron, Magnet Trimming Coil - Base Assembly, Perimeter Stiffening Web, 1960
[xiii] http://www-nsd.lbl.gov/LBL-Programs/nsd/user88/chchist4.html

Chapter 3

Displacement analysis of the magnetic poles due to magnetic and vacuum forces

Summary

A finite element analysis (FEA) of the iron structure, the 88-Inch Dee tank and the resonator tank was conducted. The FEA structural model was utilized first to explain the magnetic field dependence of the vacuum performance of the 88-Inch Cyclotron[i] and secondly to design a new improved vacuum Dee tank. Finite element analysis was used to model the magnetic and vacuum loads on the seal region as well as the Dee tank and resonator tank. The results from the FEA were compared to actual measurements of displacements of the magnetic poles. Reasonable correlation between the calculations and the measurements could be found. The results conclusively explain the observed correlation between the magnetic field and the vacuum and establish the displacement of the magnetic iron poles due to magnetic force as the cause of the magnetic field depended vacuum leak of the Dee tank.

3.1 History

The LBNL 88-inch Cyclotron was built in the early 1960's and has been continuously operated for over 40 years. However, vacuum leaks have existed since the startup in 1961. The main vacuum seals between the iron pole pieces and the vacuum tank plate have been identified as the primary cause. Attempts have been made over the years to plug this leak by accessing the seals via the pump out ports. The ports have been filled with liquid sealants, permatex and even vacuum grease. These "remedies" seem to improve vacuum temporarily, but the most consistent improvements in vacuum have been observed when the main magnet coil current exceeds a threshold value. The relationship between magnet and improved vacuum has been consistent even though the steel yoke and poles have been cycled thousands of times under both magnetic and vacuum loads.

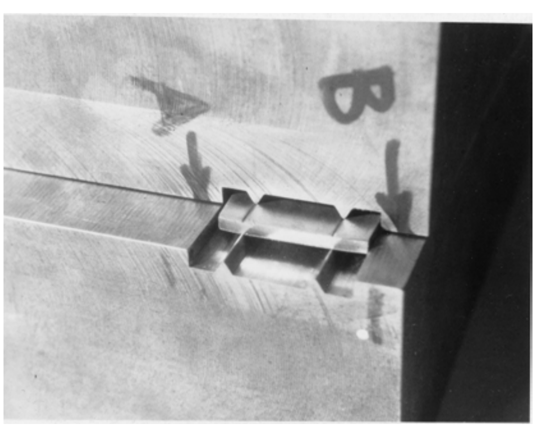

Figure 3.1 Main vacuum tank knife-edge seal (test piece) between the pole pieces and the vacuum chamber top and bottom plates.

The structure of the yoke and stud assembly has been designed to maintain a constant pole gap even under very high magnetic force loads. As noted in the original 1959 design engineering notes[ii], the expected load on the poles at 17 kgauss was 1,040,000 lbs. At this load, the relative displacement of the pole to the built in portion of the yoke (where the yoke attaches to the leg) was calculated to be only 0.00045 inch and did not include the vacuum load, which adds 90,000 lbs per pole. This displacement would be negligible for the vacuum seal and the design was though to be very conservative. Displacement measurements of the gap between the upper and lower yokes were performed 1996 using dial indicators on the outer edge of the iron yoke and showed a maximum displacement of 0.0019 inch at a main coil current of 1800 amps. A maximum displacement of 0.0042 inches was measured at 2400 amps. These displacements are substantially higher than originally thought but were still too small to explain the vacuum leaks. All the results are listed in Appendix 1.

For this study, the motion of the yoke was measured closer to the middle of the yoke where the greatest displacement would occur using a laser tracker (see figures 3.5 through 3.7). These measurements in combination with the Finite Element Analysis have shown displacements by an order of magnitude higher than estimated in the original design in 1959 and can conclusively explain the relation of the vacuum condition to the cyclotron magnetic field.

3.2 Finite Element Model

3.2.1 Mechanical Geometry

The present mechanical and structural configuration of the 88-inch Cyclotron has been derived from the original construction drawings and upgrades. It was determined that a fully comprehensive ProE CAD model would facilitate the design of any upgrades or repairs. The ProE model shown in Figure 3.2 is an example of the accurate representation used as the basis for finite element analysis performed using the FEA tools such as ANSYS 7.0 Workbench.

3.2.2 Input of the magnetic field

A magnetic field map, shown in Figure 3.3, measured for 1567 amps of current through the main magnet coil was used to develop a ratio between current (amps) and magnetic field strength (kgauss) over the magnet linear range. For this particular current setting the magnetic field varies between the hills and the valleys in the cyclotron from 18.7 kGauss to 10.96 kGauss as shown in the plot. For simplicity, an average field of 15.4 kGauss was used for the FEA analyses. For the other field settings the ratio of the average field/main coil current at 1567A (factor of 9.818E-03) was used to scale the field strength in kGauss. The field strength was then converted to a pole face pressure and used as a load in the FEA. See Eqn 1 and Figure 3.4.

$$PoleForce(psi) = \frac{1}{1.174}(kgauss)^2 \qquad (3.1)$$ [iii]

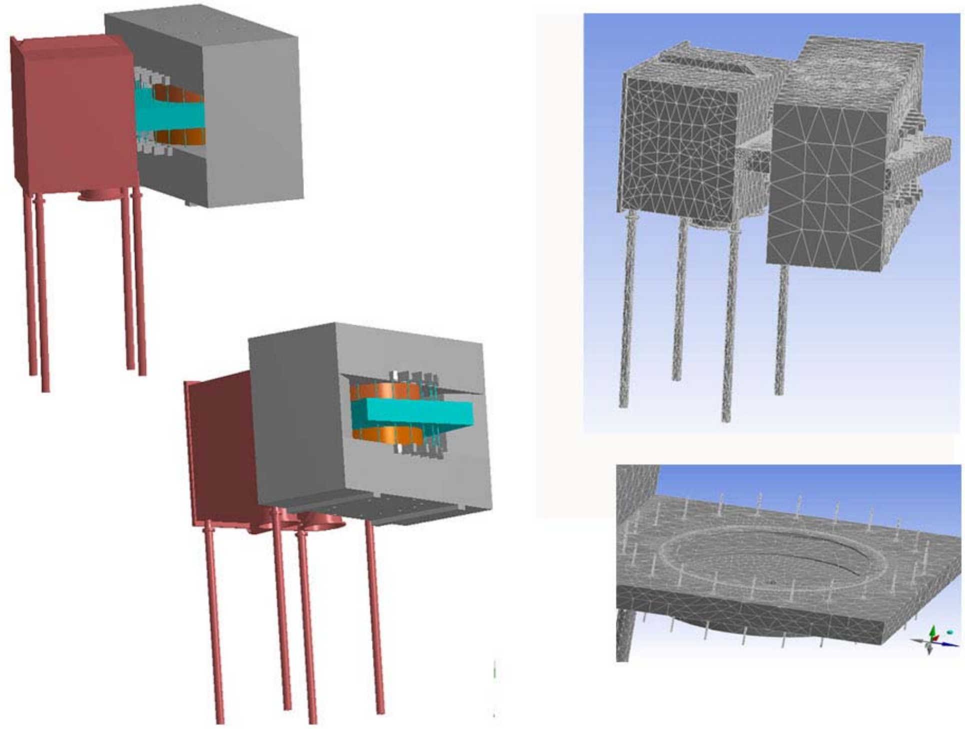

Figure 3.2 ProE Geometry and ANSYS FEA mesh of 88-inch Cyclotron. The mesh density has been increased in areas around the knife edge seal. Bolted joints are modeled as solid connections because of large preload on bolts.

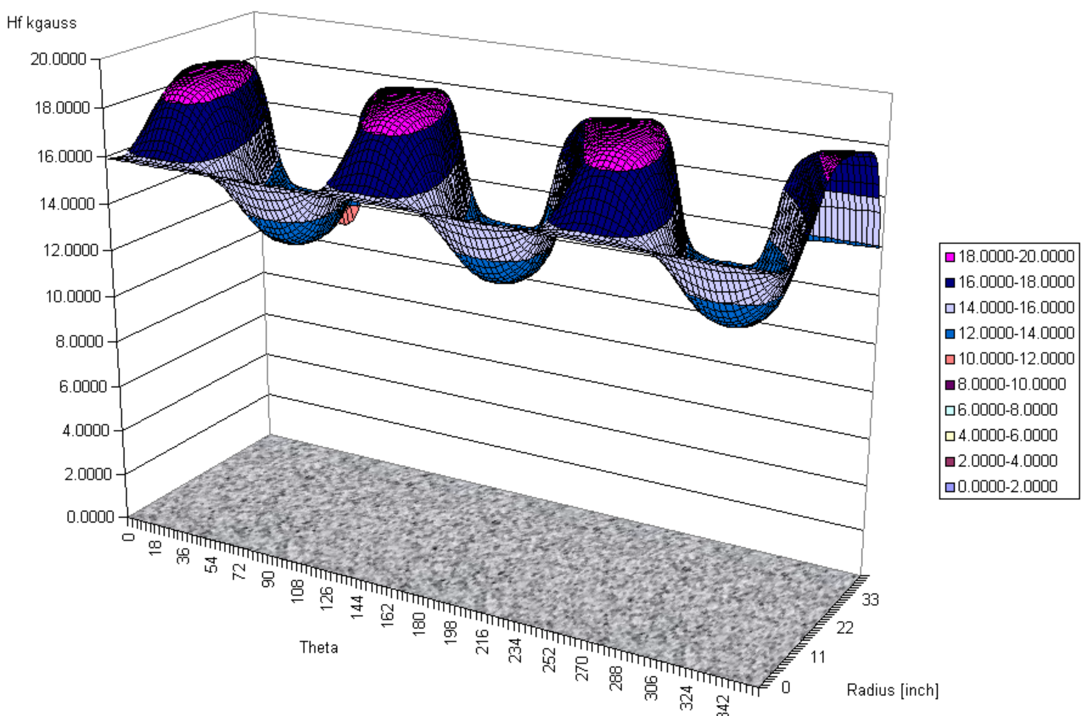

Figure 3.3 3D plot in Cartesian coordinates of magnetic field at 1567 Amps

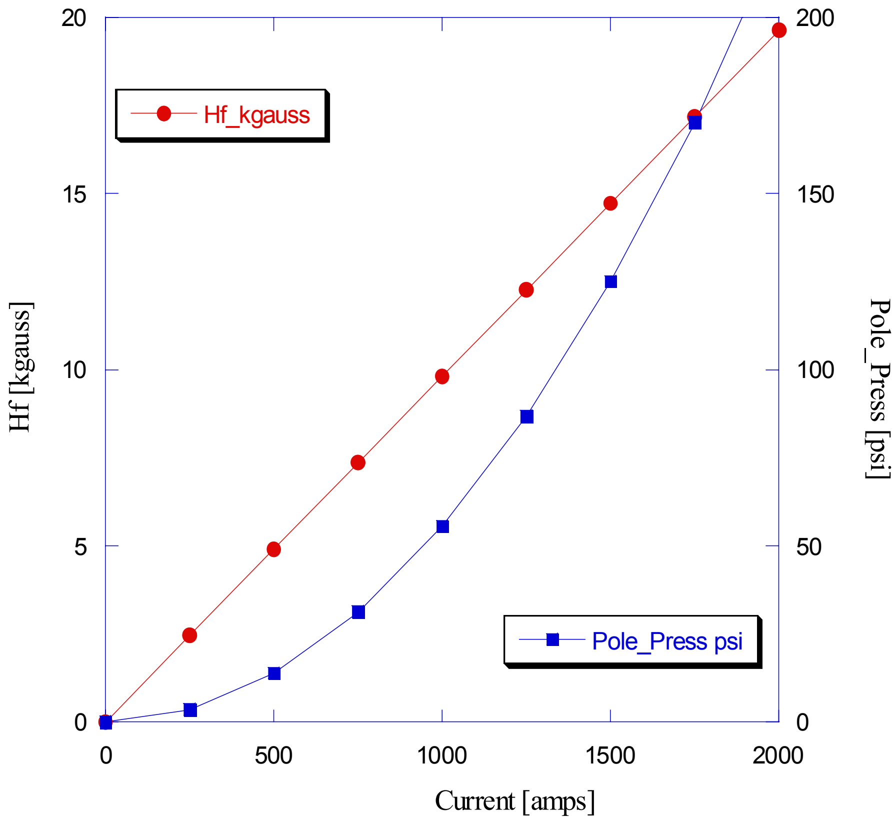

Figure 3.4 Relationship between magnet current (amps), average field strength (kGauss) and pole pressure (psi)

3.3 Numerical Results

An example FEA results for vertical displacement are shown in Figure 3.5 and Figure 3.6 at a main coil current of 0 amps and 1567 amps respectively.
The motion of the upper pole and the improvement in vacuum seems to indicate that there is an improvement in the upper and lower main seal as the upper and lower magnet pole move towards each other by up to 0.007 inch.
This result is within the same order of magnitude as analytical calculation, which give about 0.01 inch for the upper pole (with point loads for gravity, vacuum load and pole face forces) and half of that for the lower pole. The lower pole moves less because it is rigidly mounted to two large concrete pillars.
The numerical results are graphed in Fig.3.8 and compared with the measurements.

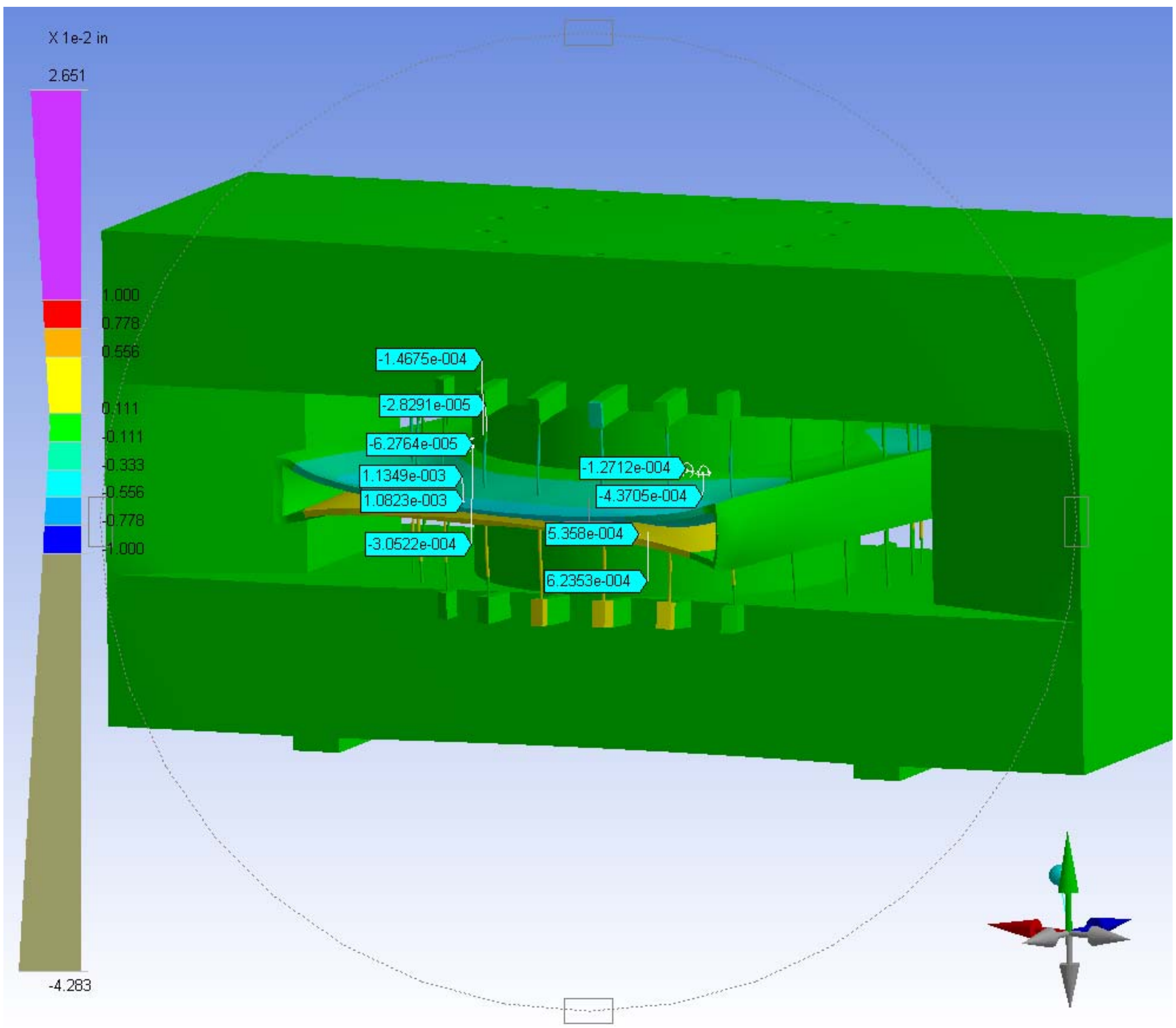

Figure 3.5 Y-Axis (vertical) displacement of Yoke, Vacuum Tank and Magnet Poles at 0 amps with vacuum load and gravity load., displacement is given in inches.

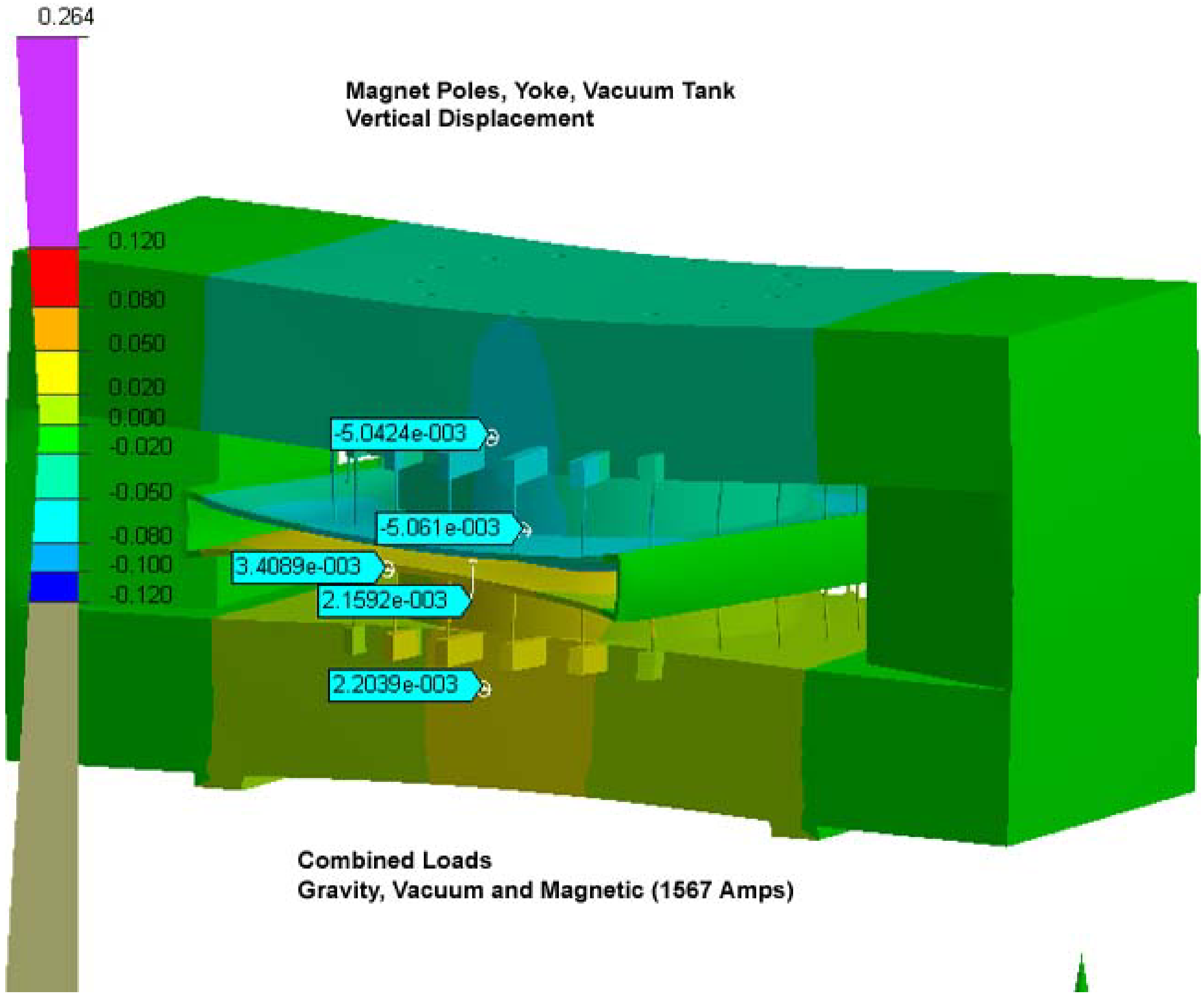

Figure 3.6 Axis (vertical) displacement of Yoke, Vacuum Tank, Poles and Yoke at Magnet Current 1567 amps., displacement is given in inches.

3.4 Measurements

Displacement measurements were performed in March of 2003 using a Leica LTD500 laser tracker. Following the results of the initial FEA analyses, the motion of the yoke was measured closer to the middle of the yoke where the greatest displacement would occur (see Fig 3.4 and 3.5)
The setup for laser tracker measurements is shown in Figure 3.7 and the measurement coordinate locations are in Table 1. The results of the measurements are shown in Fig. 3.8 and are compared with the results from the FEA analyses.
Table 1 Target location – x,y coordinates

Target ID	Location	x (in.)	y (in.)
A	Upper Yoke West Edge	-42.491	1.290
B	Upper Vacuum Tank South	1.760	-58.624
C1	Upper Vacuum Tank South	28.098	-58.397
C2	Upper Vacuum Tank South	23.116	-60.951
2	Upper Yoke south edge	19.817	-115.911
3	Upper Yoke southwest Corner	-42.501	-115.911

3.5 Discussion

In comparing the displacements measured by the laser tracker with the results from the FEA, the FEA had smaller displacements. Nevertheless, they are in agreement within the error bars of either result. The lower displacement from the FEA result is not surprising and consistent with simplifications made in the cyclotron model. In the FEA, the bolted joints between the yoke legs, the yoke upper and lower slab and the poles pieces were modeled as a monolith (rigid bonded connection) instead of a bolted joint. This was a reasonable assumption since the displacements were small and the pieces were joined together under very high stud pre-tension. In the physical system these connections may have some compliance and are only as good as the actual stud tension connecting all the components. This being said the displacement plots in Fig. 8 show that the slopes of the FEA and Laser tracker measurements track very well. The magnitude of the displacements also correlated well with hand calculations that considered the full span of the unsupported yoke beams from leg to leg. The original design calculations used only a portion of the span and predicted much smaller displacement based on the Engineering Note design calculations.
Compared with the results calculated from finite element analysis displacement at the knife edge seal upper and lower poles versus current (left scale). Average vacuum measured as graphed in Figure 1 is also added as reference (right scale).

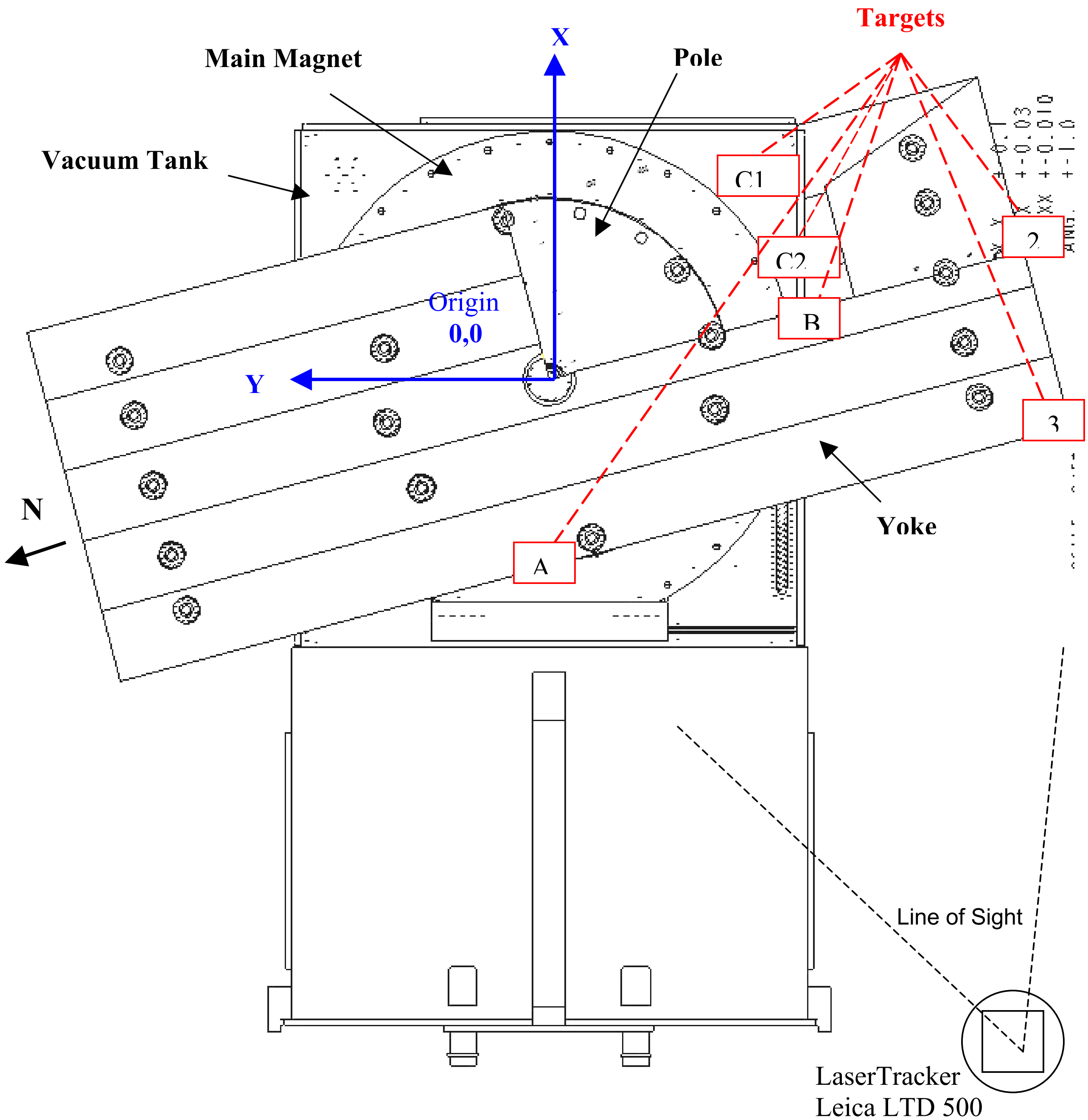

Figure 3.7 Target (corner cube) locations to measure displacement of yoke and tank. The yoke is shown in cutaway to show target locations on vacuum tank. Target locations given in Table 1 are relative to (0, 0) which is located on the injector center bore for the tank. The Leica LTD500 laser tracker was positioned on a stand 8 ft. high in the southwest corner of the vault.

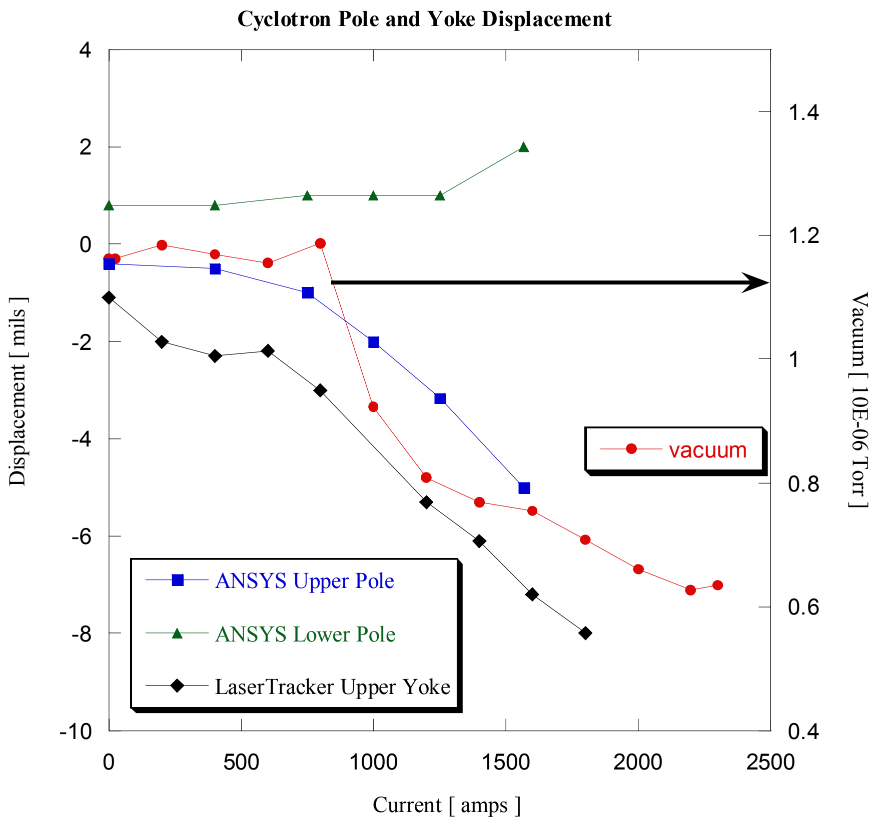

Figure 3.8 Measured z-axis displacement at the upper yoke.

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[i] TBD find reference
[ii] R. Peters, LBNL Engineering Note # 7331-04, 88" Cyclotron Magnet Core Design Comments, 3/31/59
[iii] LBNL Engineering Design Data #56C

Chapter 4

Design of the New Dee Tank

4.1 Original (Current) Dee Tank Design

Figure 4.1 shows the 3D assembly drawing of the 88-Inch Cyclotron. The hardware components that make up the Dee tank vacuum envelope are highlighted in the drawing. These are also the components, which we are proposing to be redesign and replace. The Dee Tank consists of six separate stainless steel plates (see Fig 4.2). The upper and lower Dee tank plates are knife-edge sealed against the upper and lower iron poles. The side plates and corners are sealed with an elaborate system of double wire seals, bolt seals on every bolt and a multi-part corner seal. The separate components of the Dee tank are shown in Figure 4.2. The Dee vacuum tank is not fully assembled at one time. The top and bottom plates are installed during the magnet coil, pole and yoke assembly. The resonator tank is then attached to complete the west section. The north, south and east side plates are installed after the trim coils, hills, Dee and deflector have been mounted inside the vacuum chamber.

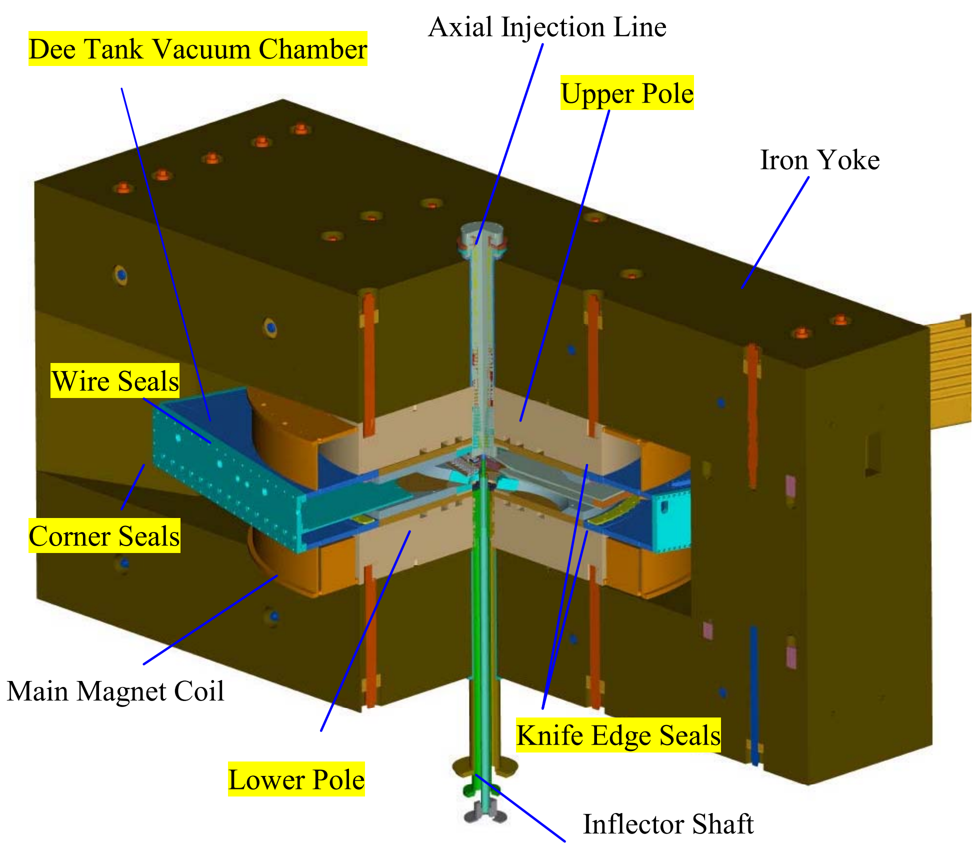

Figure 4-1 3D CAD rendering of 88-inch Cyclotron. The hardware components that form the Dee tank are highlighted.

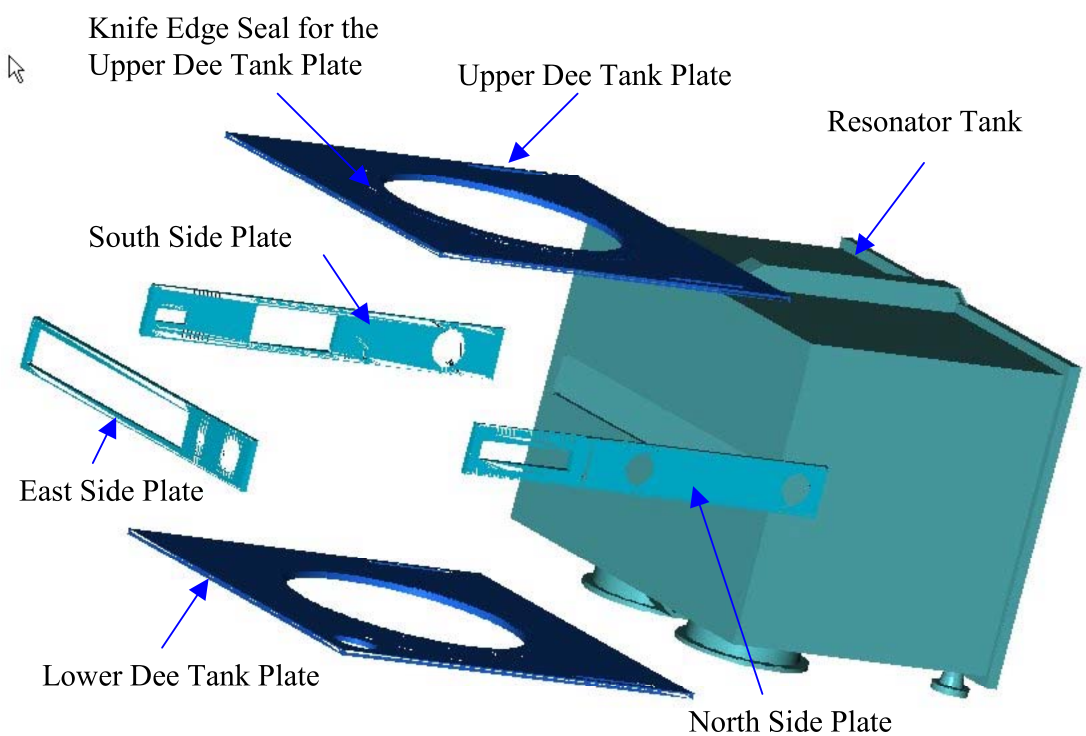

Fig 4.2. Exploded view of Dee tank.

4.2 Design of the new Dee Tank Vacuum Envelope

4.2.1 Welded Vacuum Tank Seal between the Upper and Lower Dee Tank Plate and the Iron Poles

The welded tank seal replaces the bolted knife-edge seal between the iron poles and the upper and lower Dee tank plates (see Fig.4.1 and 4.2) with a welded joint. This weld provides both the vacuum seal and the structural support and eliminates the bolted joint. The feasibility of such a welded joint has been demonstrated at the Texas A&M 88-Inch Cyclotron at Texas A&M University, College Station, Texas. The vacuum performance is independent of the magnetic field and the cyclotron has been operated for several years without developing a vacuum leak at this weld joint. However, that particular weld was integrated into the original design. Therefore, it is not directly applicable for the proposed design.

Several issues were considered to develop a new vacuum chamber design, which incorporates a welded seal. The primary concern was the feasibility and ease of the installation of the new pole, vacuum tank plate and the main magnet as a unit shown in Figure 4.3. In the original construction the pole was installed separately from vacuum tank plate and Main Magnet coil assembly (see Chapter 5, Disassembly and Assembly Sequence of the Cyclotron). With the welded joint, the new assembly has a combined weight of 19 tons without the rigging. This weight is within the capacity of the Building 88 30 ton crane.

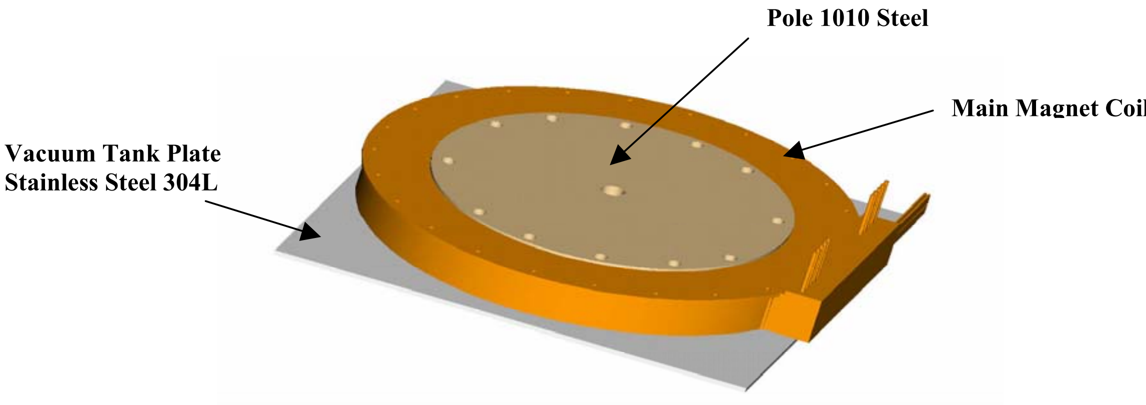

Figure 4.3 Main Vacuum Tank Assembly for the welded vacuum seal design.

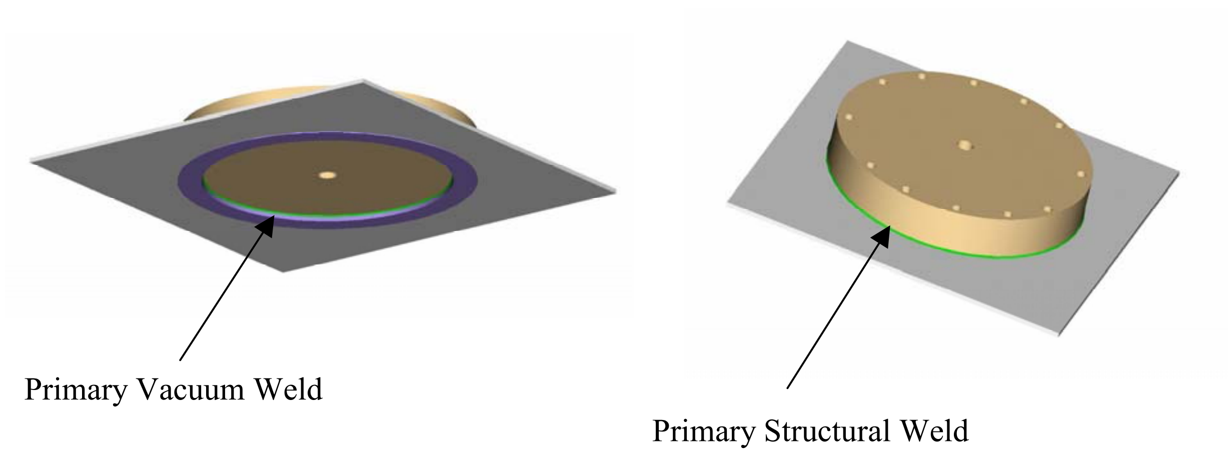

Figure 4-4 Pole and Vacuum Plate Primary Tank Welds – Vacuum (left) and Structural (right)

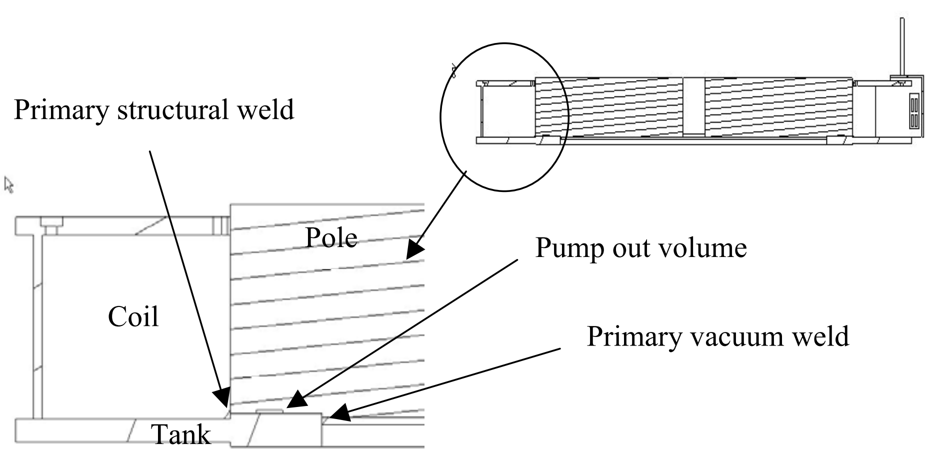

Figure 4.5 Tank weld detail with vacuum pump out volume

Another design goal was to develop a vacuum tight weldment that can survive the cyclic loading and displacement (< 0.010 inch) from energizing the magnet which can be several times per day. The design approach incorporates two welds. The first one supports the structural loads and the second inner weld provides the vacuum seal as shown in Figure 4.4. In Figure 4.5, the pump out volume required between the welds is shown.

4.2.1.1 Analysis of Welded Tank

Several design concepts for the tank weld were analyzed using finite element analysis. The analysis was used to get a qualitative assessment of the stress induced by the motion of the pole during operation. As shown previously in Figure 3.8, the pole can move up to 0.010 inches vertically. With the main magnet coil bolted to the vacuum tank stiffening is provided to the plate, which affects the stress distribution to the welds. An analysis showing this affect with a displacement of 0.010 inch is shown in Figure 4.6 through 4.7. Two conditions were analyzed. One analysis assumed a rigid coil attachment and the second analyses was done without the coil. The right plot shows the analyses without the rigid connection and the left plot includes the stiffening effect from the magnet coil. However, the physical main magnet connection is spring loaded between the main coil cover plate and the vacuum tank plate. The coil itself is not attached to either plate[i] but there are 23 3/4 inch studs attaching the main coil cover plate and the vacuum plate. The main coil cover plate is also bolted to the yoke with ½ inch SHCS. It would be difficult to model this mounting scheme accurately, but by modeling the two simplified configurations a qualitative understanding could be developed, which is sufficient for this preliminary layout. This analysis showed that the reaction force at the tank wall connections varies with the stiffness of the plates. The stiffer the plate the higher the loads at the tank wall weld.

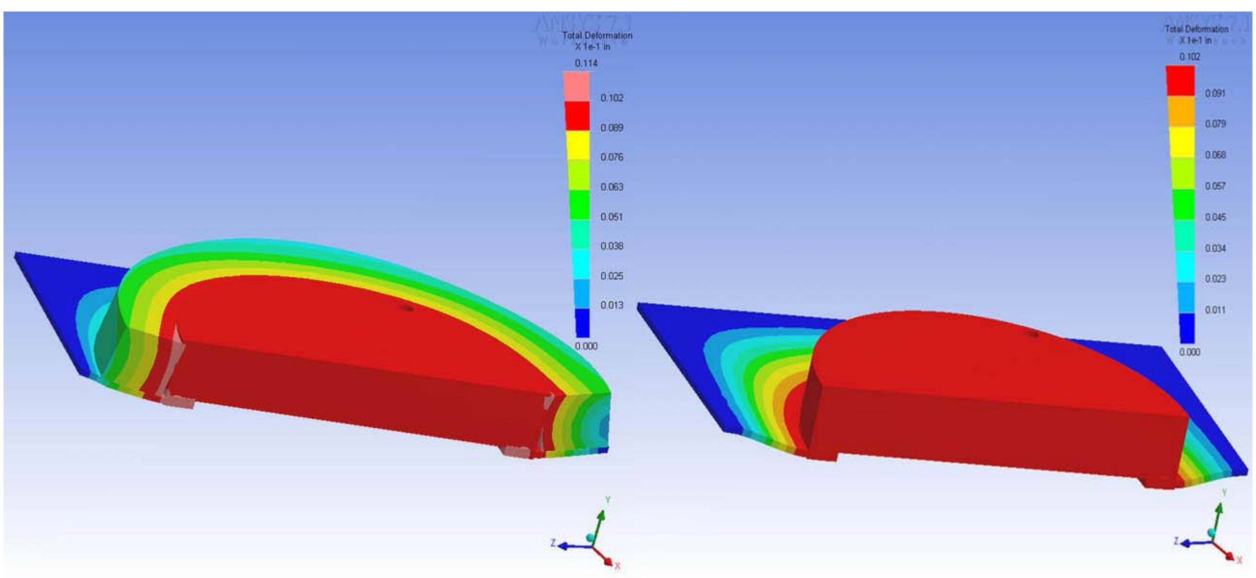

Figure 4.6 Welded Tank joint deformation of 0.010 inch with rigid magnet coil to plate connection (left) and without a rigid magnet coil to plate connection (right)

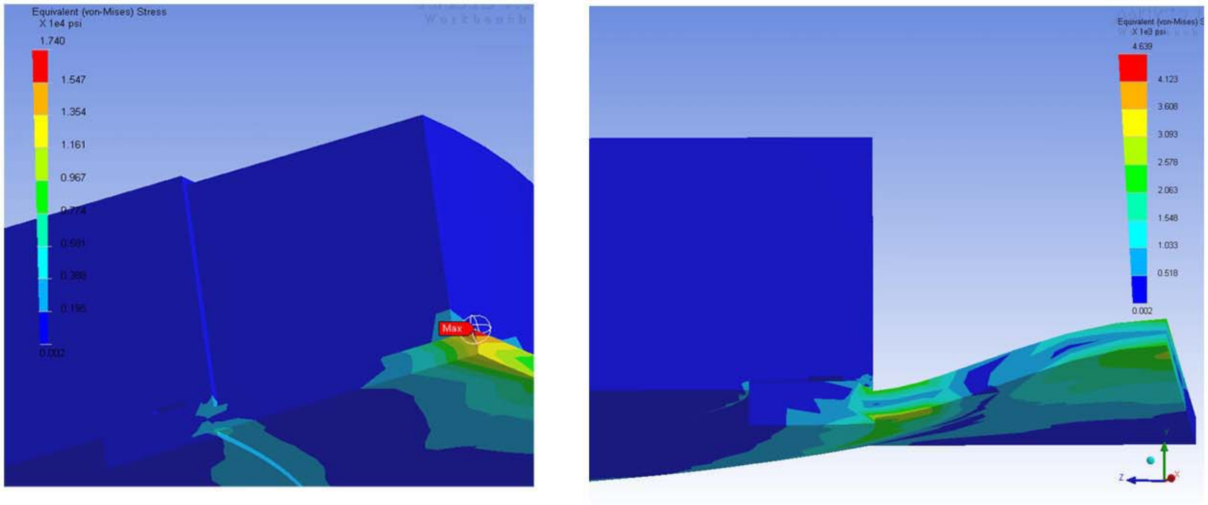

Figure 4.7 Welded tank joint stress with rigid magnet coil connection (left) and without stiffening (right)

4.2.1.2 Weld Design

As described above, the weld seals consist of two circumferential welds, one for the vacuum seal the other one for the structural support. The final weld location and type were selected to minimize the stress and strain on the vacuum weld. During operation as shown previously in Figure 4.5, the structural weld supports the majority of the load, while the vacuum weld experiences lower stress loads. Initial analysis determined that a fillet weld should be adequate, but not optimum for cyclic operation. Therefore, the weld chosen for the vacuum seal is a full penetration ½ inch deep j-groove welded on both sides. The structural weld is a ¾ inch deep single u-grove. The weld drawing has been drawn (drawing is filed in intralink common space programs/88-Inch/ welded_tank_asm.asm). The weld detail for both welds is shown in Figure 4.8. The plate and pole are made of stainless steel 304L and 1010 steel respectively. These dissimilar materials can be welded using 309, or 310 wire with a shielded, or submerged arc welder. Both welds are accessible and can be checked using standard inspection techniques prior to assembly. It will also be important to verify that the vacuum weld is leak tight prior to assembly. A leak check can be easily performed using the provided pump out port.

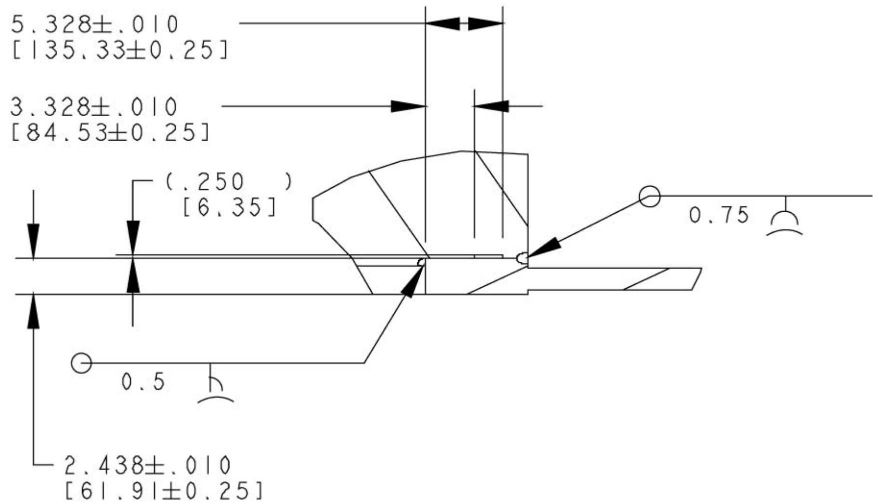

Figure 4.8 Vacuum J-Grove Weld detail Structural U-Grove Weld detail

4.3 New Seal Concept for the Dee Tank Side Plates and the Corner Seals

The new design replaces all the original wire metal seals and the corner seals with a continuous seal rated to the low 10^{-8} torr range (See Fig. 4.9). Two possible seal materials can be used. It can be either an O-ring made from a radiation resistant Viton, or EPDM P.C., or a metal seal using 0.010 inch thick 99.999% pure tin foil. Since The 88-Inch Cyclotron vacuum chambers are not baked out for ultra high vacuum applications or experience high temperature environments, either material would work at this vacuum pressure.

Although both materials are capable of being used for the continuous seal across all six separate pieces, each material has different advantages and disadvantages. The advantage of an o-ring is that it has been demonstrated to work in the 400 MHz RFQ. The o- ring would be easier to fabricate with a vulcanization process to make the joints. The metal seal will require some R&D to assure the tin could be joined to form the seal, but if proven viable will have significantly lower out-gassing and permeation than an o-ring. In addition, a metal seal will be less susceptible to degradation over time and tin seals have demonstrated very low creep.

For both options, the Dee tank will need a redesign to accommodate the new assembly.. The resources estimates for this redesign are summarized in the Chapter 9 ‘Schedule and Cost’.

4.3.1 Continuous O-Ring Seal

The concept of using a continuous seal on a six sided box structure first successfully demonstrated in 1986-87. The seal was developed for a 400 MHz RFQ research program at LBNL[ii,iii] using a 0.125 inch viton o-ring. In this concept, the o-ring joins to form a tee at the intersection of the perpendicular surfaces as shown in Figure 4.9. The R&D for this seal determined that an effective seal groove transition at perpendicular surfaces should not be sharp (as shown in early drawings). The transition needed a very small bend radius. The proper bend radius will need to be determined for this application and o-ring size chosen.

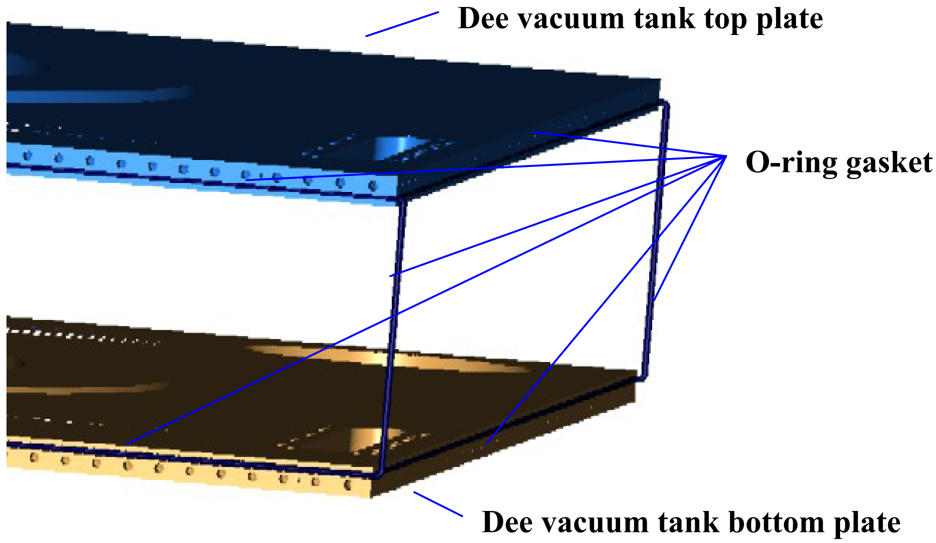

Figure 4.9 Seal configuration for Dee tank.

4.3.2 Tin Foil Metal Seals

The use of metal seals for UHV applications such as conflats are an industry standard. These seals are used typically for standard size flanges, or regularly used shapes. Using metal seals for the types of surfaces found on the Dee tank would require custom sizes and shapes. The 0.010 inch thick foil comes in 5 lb rolls up to 20 inch widths which could accommodate the 16 inch tank height.
LBL started to use tin foil for special applications when other metal gasket materials were failing (especially with bake out requirements). LBNL has successfully developed techniques for using tin foil as a metal seal gasket[iv] and has extensive experience of how to design the sealing surfaces. There are many examples at the Advance Light Source and with B-Factory at SLAC using these seals at vacuum pressures to the 10^{-10} torr range. Tin provides a significant performance advantage over other gasket metals such as gold, indium, or even copper because it has demonstrated very little creep, thus it maintains the seal integrity over a long time and multiple loading cycles.
To use the tin seal on the Dee tank would require some R&D to examine how to overlap the foil to develop a good continuous seal, but the LBL personnel[v] experienced with this material felt that an overlapping foil gasket could be made. The main disadvantage of this type of seal is that it can't be reused.
Some of the specifications and issues with working for the tin seal are listed below:

- Tin purity is 99.999%.
- Foil thickness is 0.010 inch.
- Proud sealing surface width ranges from 0.065 inch to 0.250 inch, where 0.125 inch is ideal.
- Keep sealing surface equidistant to clamping bolts to prevent warping of flange.

- Use high strength non-magnetic bolts (e.g. if possible use standard sizes available for conflats).
- Minimize Plate warping and sealing surfaces should be parallel at full torque.
    - Use “Boxer Flange” sealing surface[vi].
    - Place a sealing land feature on the bolt side opposite to the gasket area to prevent the flange from bending under bolt load.
    - Bolt torque should compress gasket about 10% to 20% (requires R&D)

4.3.3 Plate Redesign

Each of the plates will need to be redesigned to accommodate the new sealing surfaces and eliminate the corner seals. The top and bottom plate require a vacuum seal detail along the perimeter. The side plates are also longer and the end surfaces on the north and south plate will be reworked to add a vacuum seal detail. The following figures show the location of the seals and the general changes to the plates. The seal detail will depend on the type of seal chosen. The O-ring will have a groove as shown in Figure 4.10 and the metal seal will have a proud surface as shown in Figure 4.11. In addition to the sealing surfaces other features will also be changed. With the elimination of the corner seals, the north and south plates will be lengthened to match the top plates.
The seal between the resonator tank and the Dee tank will need to be modified also. The most difficult seal to install is the vacuum joint between the side plate and the resonator tank, since it has to be installed blind. Special attention will be needed to insert the seal and a careful sequence has to be developed of how to torque the bolts of three other seals at the resonator tank, the top and the bottom plate simultaneously. This process will require R&D and a test phase for installing these seals.

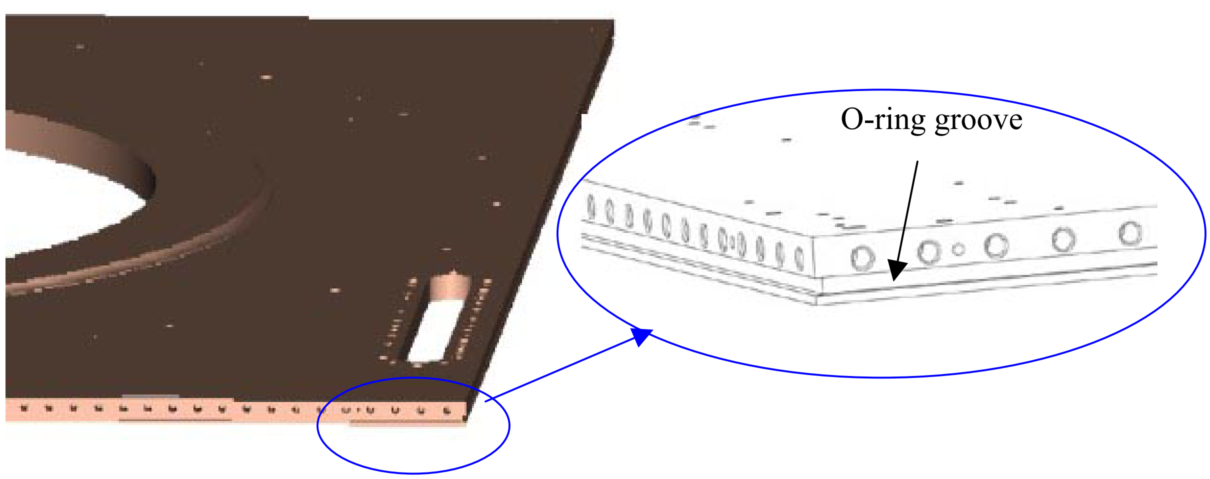

Figure 4.10. O-ring groove detail.

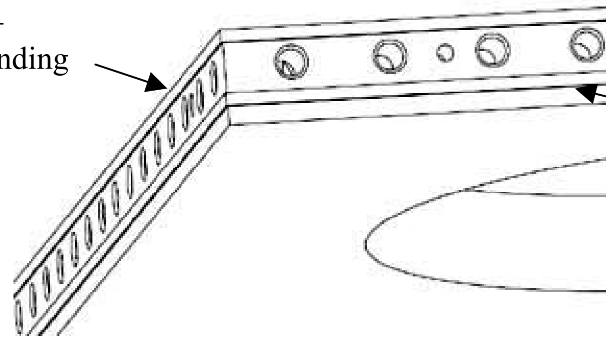

Figure 4.11. Tin Seal proud surface detail.

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i LBNL Dwg No. 9B4525, 88" Cyclotron, Magnet Main Coil, Assembly Cross Section. 11/16/59

ii Principles on this project were Steve Abbott, Robert MacGill and John Staples all from LBNL

iii Several drawings were made of the 400 MHz structure gasket test plates LBL Dwg. Nos. 22G0403, 22G0413, 22G0422, 12/1986. The 400 MHz structure assembly layout drawing is 22G0676

iv LBL Drawing #, PEP II LER-Vacuum, Pumping Chambers, Entrance End Shipping Flange.

v Private conversations with Kurt Kennedy, Tom Miller and Dan Colomb

vi A technique to put a slight angle (1/2 deg) on a sealing surfaces prior to loading so that under full torque the sealing surfaces on parallel. Developed by Tom Boxer at LLNL.

Chapter 5

Disassembly Sequence of the Cyclotron

5.1 Overview

The following sections discuss the disassembly of the 88-Inch Cyclotron prior to the upgrade and assembly of the upgraded cyclotron. The B88 archives were searched for a procedure for disassembly; although, one should exist, a complete procedure was not found. The described disassembly procedure was generated by reverse engineering the assembly process, which was reconstituted using the available historical archives of the 88-inch Cyclotron. The documents reviewed were engineering design notes, detail assembly drawings, archival photographs and articles in the "yellow book", "Sector-focused Cyclotrons"[i]. All this information was used to create a 3D CAD drawing of the assembly. The 3D cad drawing provided the ability to virtually completely disassemble the cyclotron for the first time since it was built 40+ years prior and can be used as a base for any redesign and upgrade. An example of the 3D CAD assembly of the cyclotron accelerator structure (without the RF tank) is shown below in Figure 5.1.

A cost estimate from LBNL Facilities was obtained for their effort to remove and replace utilities, the experimental injection systems from the roof, the vault shielding blocks, the cyclotron itself and seismically upgrading the shielding blocks. This facilities' estimate does not include any labor cost for facility personnel for component disassembly, installation and decontamination. These costs are rolled into the programmatic costs for the upgrades to the cyclotron discussed in Chapter 9 'Cost Estimates and Schedule'. This section will also examine areas for reducing the costs for the upgrade.

5.2 The 88-Inch Cyclotron Hardware

The 88-Inch Cyclotron is a massive steel and copper experimental device. The AISI 1010 steel for just the yoke and pole assembly of the cyclotron weighs 259 English tons. The copper for the upper and lower main coil magnets is about 4.2 tons each. The resonator tank has been estimated at 23 tons. In the vault area, the more than one hundred concrete wall and roof blocks used for shielding can weigh close to 30 English tons each. Figure 5.2 shows a picture of the 88-Inch cyclotron and Figure 5.3 shows a plan view of the 88-inch Cyclotron accelerator facility with a cyclotron vault and experimental caves.

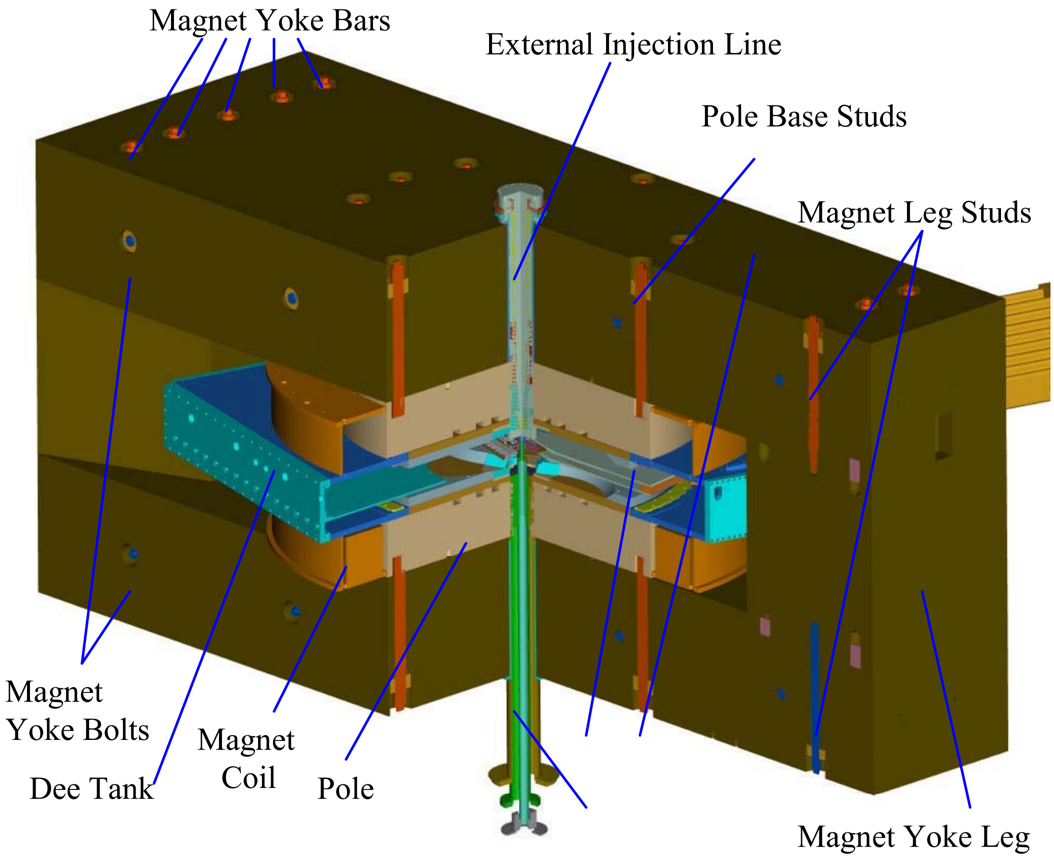

Figure 5.1 3D CAD rendering of 88-inch Cyclotron

Figure 5.2 Picture of the 88-Inch Cyclotron vault, prior to block removal. View from southwest looking towards the Cave areas.

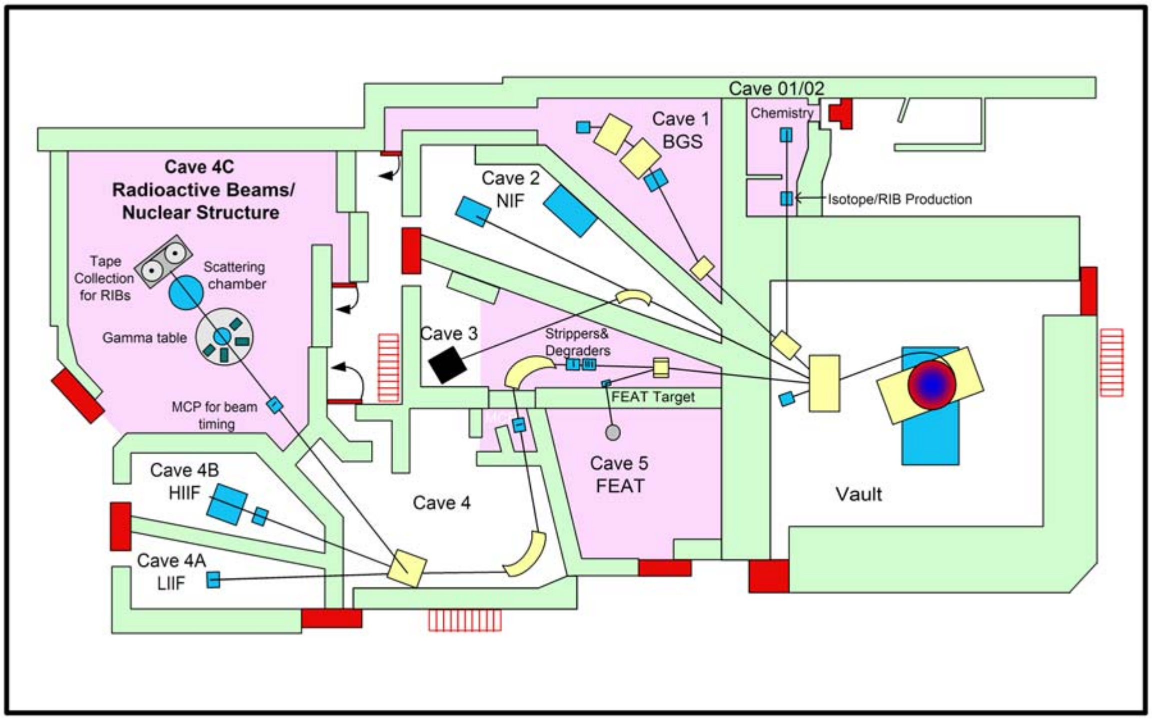

Figure 5.3 Plan view of 88-inch Cyclotron, experimental caves and shielding blocks

5.3 Disassembly of the 88-Inch Cyclotron

The timeline for the assembly of the cyclotron was documented from numbered and dated historical photos archived in 88 Inch Cyclotron Picture Archive Books #1 through #3. The photos showed that the major assembly started about mid-Nov. 1960 and the major structural components were nearly fully assembled in May of 1961 and the internal components completed later by early 1962. Using the timeline given by the picture book dates and photographs, the assembly of the yoke, poles, main magnet, resonator tank and a majority of the vacuum tank components were assembled in just over two months, from November 1960 to Mid-Jan 1961.

The original assembly of the cyclotron in the early 1960s was greatly facilitated by the fact that the shielding blocks were not installed yet. It allowed ready access for the 30 ton overhead bridge crane in the high bay to handle the large cyclotron components - the resonator tank, the dee vacuum plates, and the yoke steel. For the upgrade, the cyclotron will need to be almost totally disassembled. The only components left in place would be the bottom steel yoke and the yoke legs. Removal of the major cyclotron components will require utilization of the 30 ton crane. Therefore, the roof blocks and part if not all of the south and west wall blocks have to be removed. This would give the most accessibility and increase floor space in the high bay for upgrade work. Figure 5.4 shows the roof blocks prior to installation in the original construction.

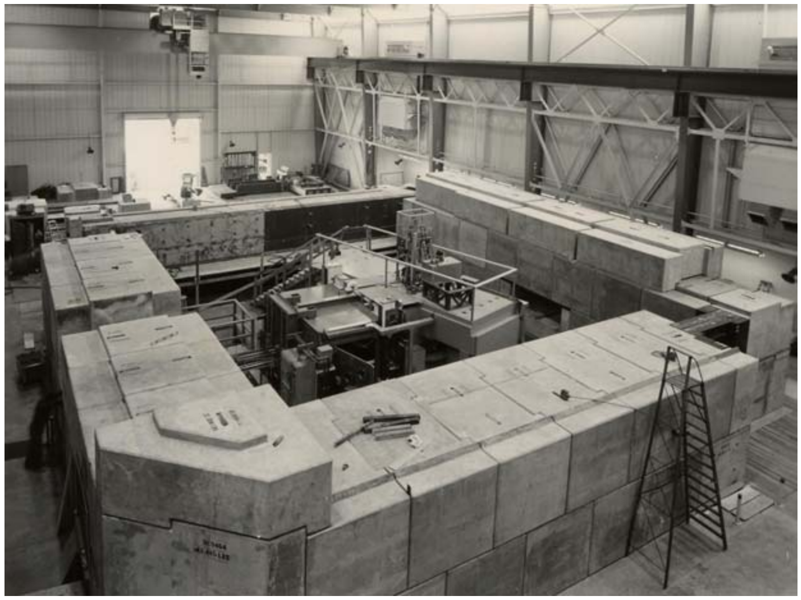

Figure 5.4. Picture book archive photo # 518, January 31, 1962. 88-Inch Cyclotron prior to installation of roof block shielding.

For disassembly today, the block removal is complicated by two factors. First, all the components and shielding blocks are considered as accelerator activated components that require special handling as radioactive material. A disassembly protocol will have to be implemented for the decontamination and safe handling of the accelerator materials deemed radioactive (both surface and volume contaminated[ii]). Secondly, there are several experiments[iii] and injectors[iv] that now reside on the roof of the shielding blocks.

Since a disassembly procedure of the Cyclotron will be was not found, the 3D solid models was used to develop a sequence. Figure 5.8 illustrates some major steps of the disassembly for the cyclotron main magnet, poles and Dee tank. Table 1 contains the complete list of all steps and includes time estimates. Several other items were included such as the beam staging line and the axial injection line. The injectors ECR, AECR and VENUS are not listed but must be removed along with the utilities from the roof prior to removing all the roof blocks.

It is worth mentioning a few cost driving components of the disassembly process. The resonator tank needs to be lifted out of the pit as one large item. In addition, the Dee assembly (Dee plates and Dee stem) and the trim coil tray assembly are two large internal components that need to slide out horizontally from the cyclotron.

As shown below in Figure 5.5, the Dee stem assembly is cantilevered on a wheeled support structure used for support during the installation and removal. Using this large wheeled support requires partial removal of the west wall blocks.

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Figure 5.5 Archive photo of Dee installation. Dee is installed into vacuum tank through Resonator tank with west wall partially assembled.

The trim and valley coil trays and the deflectors are removed from the east side and the trim and valley coil tray may require partial disassembly of the east wall to clear the tray from the tank. In Figure 5.6 below the trim coil tray is being installed prior to the east wall blocks being installed. It is unknown why the trim coil tray was installed from this end, but the process could be streamlined if it can be taken out and reinstalled from the west end. This would eliminate the need to remove any east end shielding blocks. Further assessment should be done prior to the disassembly.

Another large and awkward item that needs to be moved is the resonator tank. The 9 ft. girth of the tank requires that the tank must be removed through the south wall. As shown in Figure 5.7, the resonator tank has tall support legs (overall height is 20 feet). Therefore, it would be required to remove a portion of the south wall to lift the tank out of the vault. An option that may allow the south wall to stay intact is to temporarily remove the resonator tanks support legs and lift it over the south wall. This is a viable method if the 35-Inch diffusion pumps have been previously removed from beneath the tank. This would substantially reduce the disassembly time for the south wall.

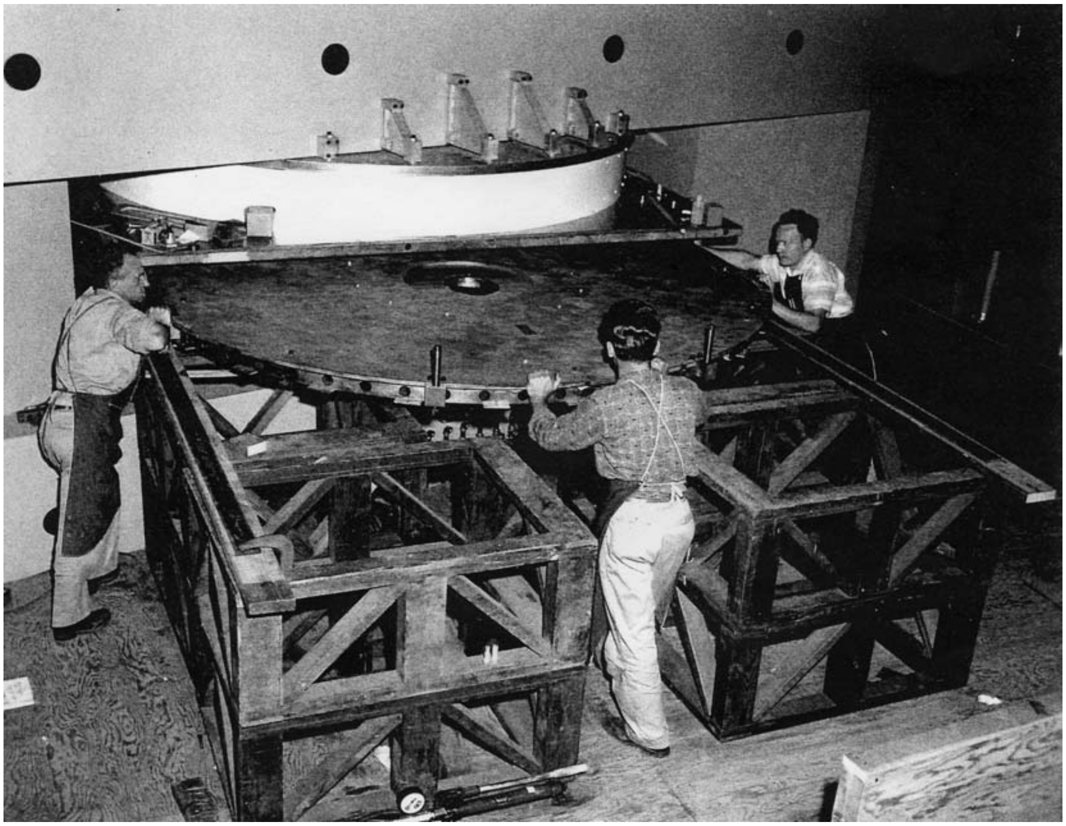

Figure 5.6 Picture book archive photo #343, April 10,1961 of Trim Coil installation on the east end of the Dee tank.

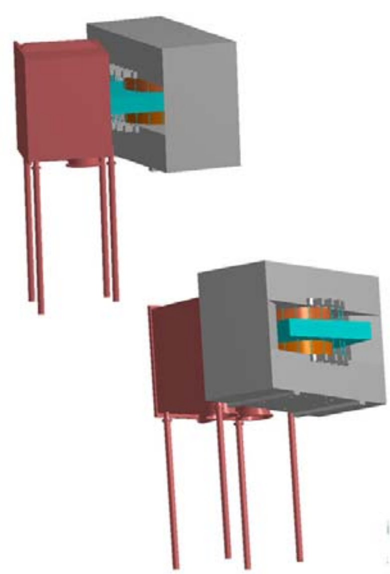

Figure 5.7 picture Book archive photo #396, May 9,1961 of Resonator tank installation. The diffusion pumps shown have since been replaced with 35-Inch diffusion pumps. For reference the CAD model of the resonator tank attached to the cyclotron accelerator is shown on the right side

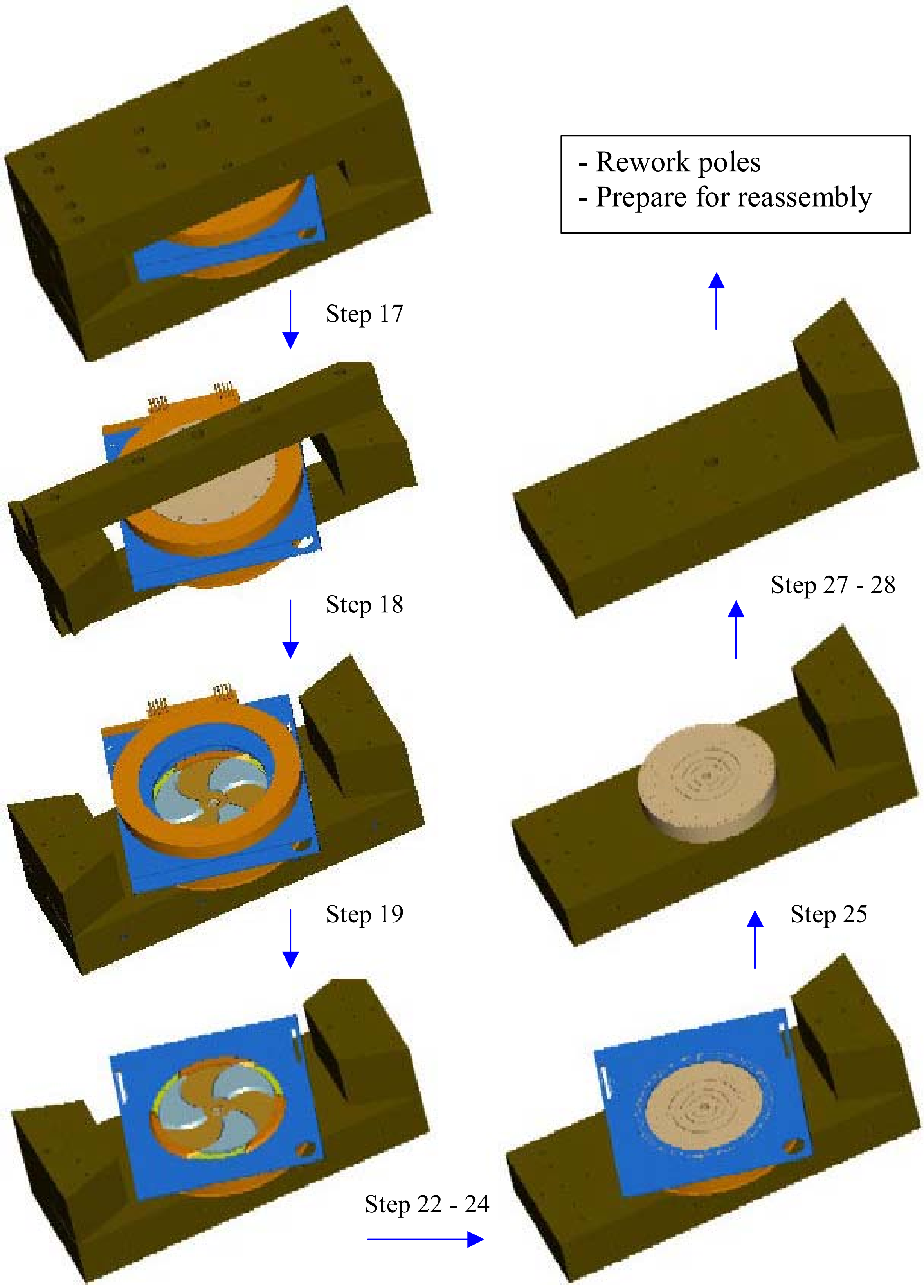

Figure 5.8. Steps 17 through 28

The poles and its supporting structure the yoke must be dimensionally stable under very large magnetic loads. At a current of 1800 amps, the force between the poles can be over $1x10^6$ lbsf. Therefore, the bolts used for assembling the yoke together as well as the connecting bolts for the pole to the yoke (see Figure 5.1) have very high preloads. The yoke assembly bolts are 2-½ inch diameter and preloaded to 165,000 lbsf. The pole to base studs are 3 ½ inch diameter and preloaded to 350,000 lbsf. To achieve these preloads a special tool and hydraulic jack will be needed (dwg no. 9B3354). The application of this tool is shown in Figure 5.9 and is used for a majority of the stud removal for both the upper and lower pole and yoke pieces. This tool, or something similar will need to be built, or purchased prior to disassembly. There is a necessary clearance to operate the tool and there is not enough headroom between the upper pole and yoke assemblies and the roof blocks to use the original tool. The picture of the full tool length is shown in Figure 5.10. A custom tool may need to be designed if the parts of the roof blocks are left intact.

Figure 5.9. Picture Book archive photo # 169, Nov. 8, 1960. Use of the bolt preloading tool on the lower pole studs.

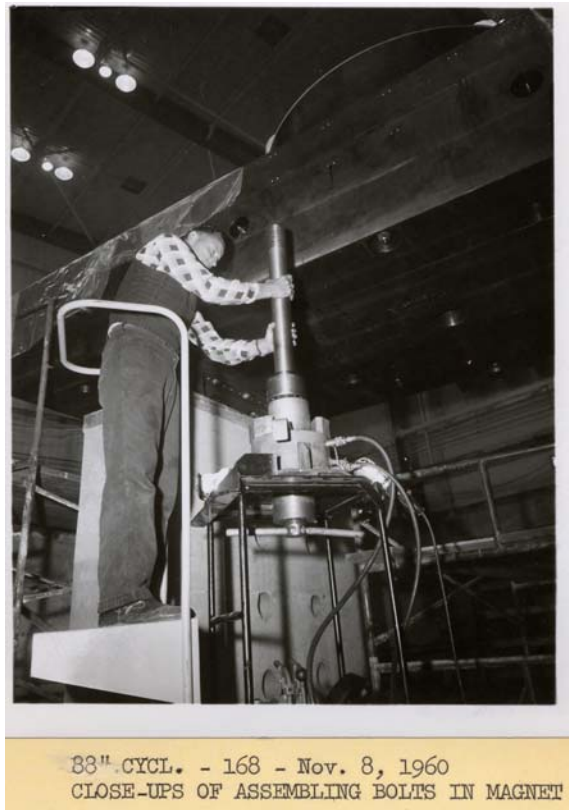

Figure 5.10. Picture Book archive photo # 168, Nov. 8, 1960. Full view of the bolt preloading tool on the lower pole studs.

Table 5.1 Outline of the disassembly steps

Step #	Part Description	Reference Dwg #	Comments	Time estimate (days)
1	Axial injection line and inflector	18M7895	LBID-2349 documentation	5
2	Beam staging line			10
3	Vacuum system		DP and Cryo Pumps	12
4	Trim valley coil cooling and elect			5
5	Main magnet cooling and electrical			10
	Lag to complete removal of AECR & Venus			TBD
6	Shielding roof and wall blocks		To be stored in parking lot	32
7	Deflector power & enclosure			3
8	Deflector and cryo / helium cryo panels		Decon required	14
9	Dee vacuum tank side walls			2
10	Dee Stem and insert		DeCon required, Remove West Shield blocks	3
11	Resonator tank		DeCon required, stored in High Bay	22
12	Decon decon trim coils and trays			10
13	Trim and Valley coils tray - upper and lower		DeCon required, Remove from east side	12
14	Decon upper and lower magnet components			10
15	Remove hill shims and mid hills to upper pole piece		DeCon required, must support upper pole assy	2
16	Main magnet coil cover plate and top plate to yoke bolts	9B4525		1
17	Remove outer upper base studs and yoke slabs	9B3606, 9B2626J	Leave center yoke bar	2
18	Remove center upper base studs, yoke and upper pole	9B3606, 9B2626J	DeCon required, upper pole to be reworked	1
19	Remove upper magnet coil and dee vacuum tank plate assy		DeCon required, Magnet is reused, plate is scrapped	0.5
20	Remove valley floor plate from upper pole piece			1
21	Remove upper magnet coil from dee vacuum tank upper plate		DeCon required, Magnet is reused, vacuum plate is scrapped	0.5
22	Remove south leg slab		Optional, provides clearance for lifting fixtures on lower coil assy	1
23	Remove outer and mid-hills on lower pole			1
24	Remove valley floor plate from lower pole piece			1
25	Remove lower magnet and dee vacuum tank plate assy			1
26	Remove lower magnet coil from dee vacuum tank lower plate			1
27	Remove lower base studs			2
28	Remove lower pole	9B3596	DeCon required, remachined	1
	Total elapsed calendar days to complete		Includes lag for injection system	~ 231

5.4 Removal of the Shielding Blocks

The cyclotron vault shielding blocks are comprised entirely of reinforced concrete. In addition, there are also steel plates used on the north wall between the vault and the experimental areas. The south, east and west wall blocks are 10 ft thick. The north wall next to the experimental caves uses a combination of 5 ft thick concrete wall-blocks and a 2.5 ft. thick steel plate. The roof shielding is 6ft.8in thick and consists of two rows of concrete blocks. The roof blocks are the biggest and the heaviest blocks at 59,000 lbs each and measure 20.5 inches wide x 40 inches tall x 62 ft.2 inches long.

Only drawings of individual block have been located, an assembly drawing, or assembly procedure for the shielding blocks could not be found in the drawing archives. It is assumed that such documents exist and it would be useful to locate these documents prior to any disassembly of the shielding blocks. These blocks will need to be brought out through the east roll up door using flatbed trucks. In order to accommodate backing of these trucks into the High Bay the LN tank mounted in the parking lot will need to be relocated.

The Facilities' disassembly cost estimate is summarized in Chapter 9 and is based on removing all the roof blocks, the entire west and south walls. Further cost savings for labor and storage could be achieved if the amount of concrete shielding blocks that need to be removed can be reduced. Some concepts will be briefly discussed below.

5.5 Options for Disassembly

The disassembly method proposed above is based on the current knowledge of the assembly process, but may not be the most cost effective or efficient. A significant savings in time and expense could be made if the roof blocks were only partially removed, or not removed at all.

The concept, in which only half of the roofs blocks are removed and the majority of the east wall is left intact, is illustrated in Figure 5.11. This option would allow the injectors to stay intact saving the removal cost, but with only half the roof blocks removed, a large portion of the cyclotron in the vault would still be inaccessible with the 30 ton crane. This option would be viable if a floor supported lifting and moving system could be used to disassemble the iron yoke, iron poles, magnet coil, main vacuum tank and deflector . The available clearances and weights of components are shown in Figure 5.12.

Another option would be to remove all the roof blocks, but leave the west and south wall partially intact to varying degrees. The primary drivers are to remove a sufficient amount of west wall blocks to extract the Dee stem and south wall blocks to relocate the resonator tank.

The design and structural supports for the seismic upgrade will also determine the extent of disassembly of the shielding blocks. It could be necessary to remove a majority of the blocks. Table 5.2 summarizes changes to improve future disassembly and reassembly.

Table 5.2 Summary of ideas to improve accessibility of the cyclotron for maintenance in the future

Accommodate limited clearances and heavy weights in the vault with – Low head clearance tools – Heavy lifting devices for use in vault – Modify roof shielding to increase head room – Integrate a crane in vault
Reusable, simple and reliable vacuum seals (see Chapter 4)

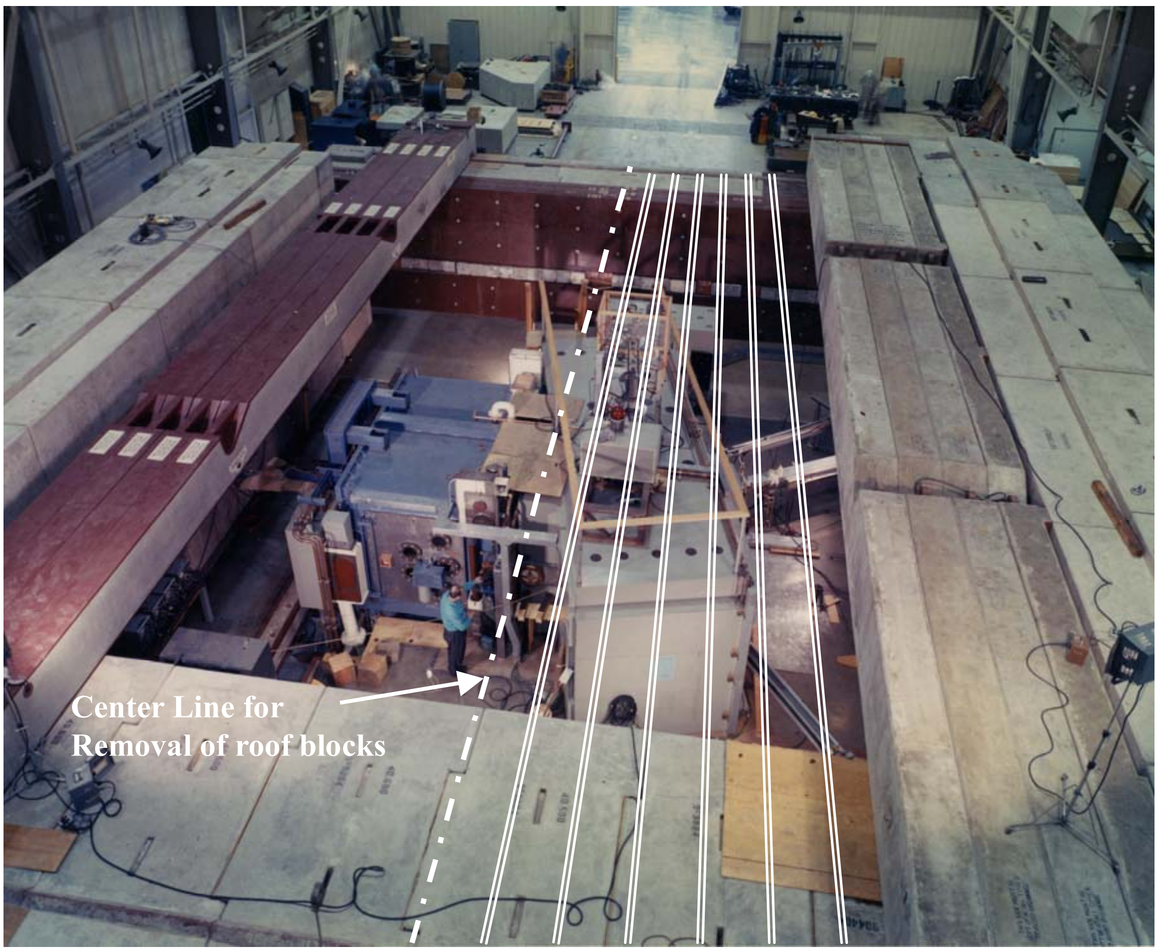

Figure 5.11. Illustration of access to cyclotron with a partial roof block removal. This photo is from the original assembly illustrating the cyclotron location relative to the roof blocks. The centerline on the roof is indicated with a dashed line. The region where roof blocks would remain illustrated with double lines. The blocks would only be removed on the left (west) of the centerline to allow the injectors on the right (east) side of the roof to remain on the roof.

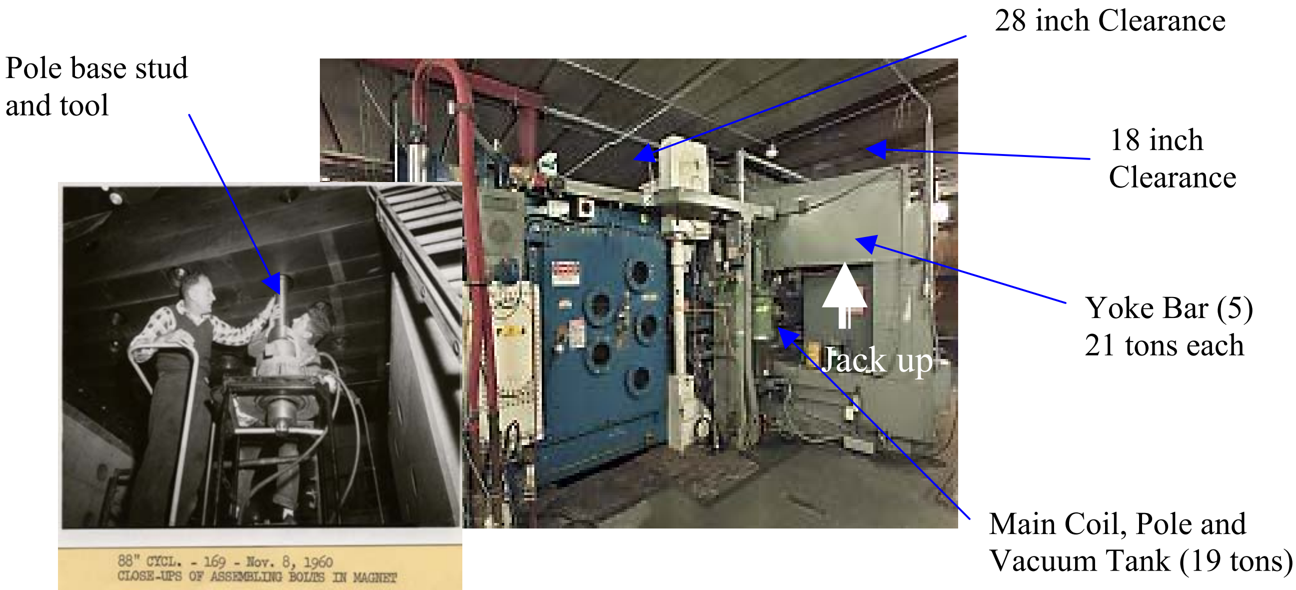

Figure 5.12 Available clearances and weights of components for disassembly of the 88-Inch cyclotron with the roof blocks intact.

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[i] K. Siegbahn, F.T. Howard, Sector-Focused Cyclotrons, Proceedings of the International Conference on Sector-Focused Cyclotrons, April 17-20 1962, North-Holland Publishing Company-Amsterdam, 1962

[ii] By DOE Order 5400.5 and Federal 10CFR835, all accelerator activated components, hardware and shielding are designated as volume contaminated. Radioactive surface contamination is typically activated material that is swipeable.

[iii] Atomic Physics North and South. Contact is Mike Pryor

[iv] AECR, ECR and VENUS

Chapter 6

Reconstruction and Reassembly of the Cyclotron

6.1 Overview

There were no detail assembly procedures available and the purpose of this section is to identify areas unique to the upgrade that should be included in the reassembly procedure. Much of the process summarized here was extrapolated from the assumptions made for the disassembly procedure. It is expected that a more detailed reassembly process will be developed from knowledge gained during the disassembly of the cyclotron. The disassembly and reassembly are integrated parts of the upgrade process. Therefore, the reassembly process steps are numbered in a continuing sequence starting from the last disassembly step #28 listed previously in Table 5.1. The basic reassembly steps #29 - #53 are outlined in Table 6.1.

The upgraded cyclotron requires several component modifications, which include the vacuum tank, poles and the vacuum system. The following list summarizes the major component changes, that have impact on the reassembly process.

1. The knife-edge vacuum seal between the pole and Dee vacuum plate is replaced by a welded joint. This requires remachining of the original pole (weld preparation).
2. Continuous seal is used for Dee tank side and corner seals. New plates for the Dee tank vacuum chamber will be fabricated to accommodate the new seal type.
3. Vacuum System Upgrade: The diffusion pumps will be replaced with cryo and turbo pump combination system.
4. Seismic Retrofit: Detail analysis and design will be needed. The seismic retrofit has yet to be designed. Once a design is in place, the process and schedule will need to be adjusted to include both the design and construction for the seismic retrofit.

6.2 Machining and Rework

The primary components that will be machined and reused, or fabricated new are the poles and vacuum tank. For the welded vacuum seal, the existing magnet poles will be machined and reused. Because the poles are activated, they will have to be remachined either on site at LBNL, or shipped to LLNL. The process has been discussed with shop supervisors from both sites and it was concluded that the ability and capacity of both machine shops is sufficient. The machining of the activated materials will need to be isolated using special HEPA ventilation. This can be set up as a temporary tented area. In addition, the milling can be performed using a portable milling head. The flexibility of this set-up increases the site options. If desired a temporary machining area can even be established in the 88 Inch High Bay. Details of both the pole welds and design of the new Dee tank are described in Chapter 4. The pole welds are shown below in Figure 6.1.

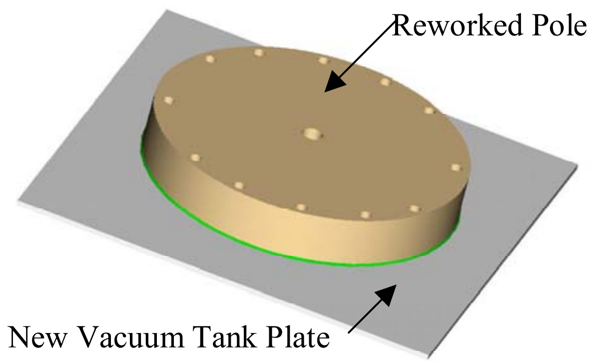

Figure 6.1 Magnet Pole Weld Assembly

The six Dee tank plates will need to be redesigned to accommodate the new vacuum seals as discussed in Chapter 4. The redesigned tank plates are identified below in Figure 6.2. The top and bottom vacuum plates are large plates (121 inch x 125.7 inch x 1.5 inch thick) made from 304 L stainless steel. The size exceeds the on-site capacity at LBNL and it will need to be fabricated in an outside machine shop.

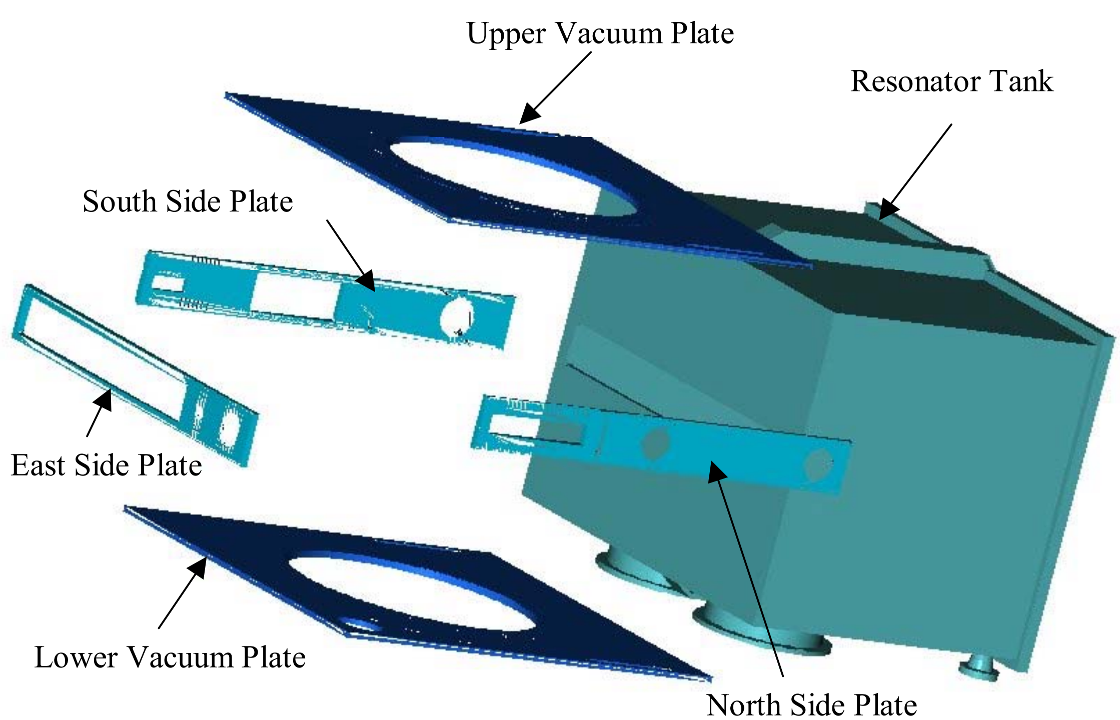

Figure 6.2 Exploded view of vacuum tank plates

6.3 Weldment – Magnet pole, vacuum tank and main coil

In the original disassembly, these parts were removed as two subassemblies with the vacuum tank and main coil comprising one assembly, while the pole was part of another assembly. With the new welded seal design, these sub assemblies are welded together and must be installed as one unit. The combined weight of this new subassembly is estimated to be about 19 tons with the rigging (Pole = 12.2 tons, Coil = 4.2 tons, Vacuum Chamber plate = 2.13 tons). This new assembly is shown as part of the installation in Figure 6.3 below.

New rigging will need to be designed to support both the pole and the plate. The engineering analysis shows that both the pole and the ends of the tank should also be supported during the lift to minimize the stress on the vacuum tank welds.

Reassembly Steps

The process steps are summarized in table 6.1. The procedure is the assembly in reverse with a few exceptions, which will be described here.

Step 29 and 34. The new magnet pole weldment now requires the pole, vacuum tank plate and main coil to be assembled and moved together as a unit. This will require a lifting fixture that should have 20 ton capacity and the capability to simultaneously support the pole and edges of the vacuum plate for both the upper and lower assemblies.

Step 30 and 35. Because the plate and pole are welded together, it allows all the shims and valley plate to be mounted to the magnet pole weldment prior to installation to the yoke. The critical issue here is to maintain the proper alignment of the upper and lower plates. The existing pre-upgrade field map is well characterized and it would be advisable to locate and document the exact present positions of the shims. This would avoid having to do an extensive field map after the upgrade. The goal is to preserve the cyclotron magnetic field distribution as consistent as possible before and after the upgrade.

Step 41. The new tank seal is a continuous o-ring that seals across all six sides of the vacuum tank. Details of this seal are given in Chapter 4. This seal must be installed on the west side of the tank prior to bolting to the resonator tank. The other sides of the o-ring are continuous so the seal is left in place in the o-ring groves prior to the north, south and east plates being installed. A temporary cover plate should be installed along the perimeter of the plate over the o-ring to protect the o-ring during assembly of the other internal components.

Step 50. As discussed previously, the seismic retrofit for the vault shielding blocks is required. The scope and details of this task has not been defined at this time.

Table 6.2 Outline of the reassembly steps

The table below provides the order in which the cyclotron should be reassembled. Reassembly will differ from the original because the Dee tank assembly has been redesigned. A new vacuum system will replace the diffusion pumps. Step # continued from disassembly table 5.1.

Step #	Part Description	Reference Dwg #	Comments	Duration (days)
29	Assemble lower main magnet to lower pole and lower Tank vacuum plate weldment	9B3596	New assembly Welded tank seal. CAD Dwgs: nuseal_dee_tank.asm, welded_tank_asm.asm	2
30	Install lower pole piece hill shims, rose shims and valley floor plate			1
31	Install lower magnet, pole and vacuum seal weldment onto lower yoke bars		Install new weldment, requires special lifting fixture	1
32	Install lower base studs			1
33	Install south leg slab			1
34	Assemble Upper main magnet to Pole and vacuum tank top plate weldment		New assembly Welded tank seal. CAD Dwgs: nuseal_dee_tank.asm, welded_tank_asm.asm	2
35	Install upper pole piece hill shims, rose shims and valley plate.			1
36	Install upper magnet, pole and vacuum seal weldment onto cyclotron		Align over lower pole and install cribbing to prep for step #39	1
37	Install center upper yoke	9B3606, 9B2626J		1
38	Install outer upper yoke slabs	9B3606, 9B2626J		2
39	Main magnet coil cover plates and vacuum plate to yoke bolts	9B4525	Upper and lower main coil	2
40	Trim and Valley coils tray - upper and lower			5
41	Vacuum Tank O-ring installation		New process	1
42	Resonator tank			12
43	Dee Stem and insert			7
44	Cryo / Helium Cryo Panels			6
45	Main Magnet Cooling and Electrical			30
46	Trim valley coil cooling and elect			5
47	Deflectors, Power & enclosure			3
48	Dee Vacuum Tank Side walls			3
49	Vacuum system		DP and Cryo Pumps	31
50	Seismic Retrofit		Design TBD	TBD
51	Install Vault floor, roof and wall blocks		stored in parking lot	35
52	Beam Staging Line			10
53	Axial Injection Line and Inflector	18M7895	LBID-2349 documentation	10
	Lag to complete installation of AECR & Venus		Estimate 190 days	TBD
	Total elapsed calendar days to complete		Includes lag for injection system	~74(TBD)

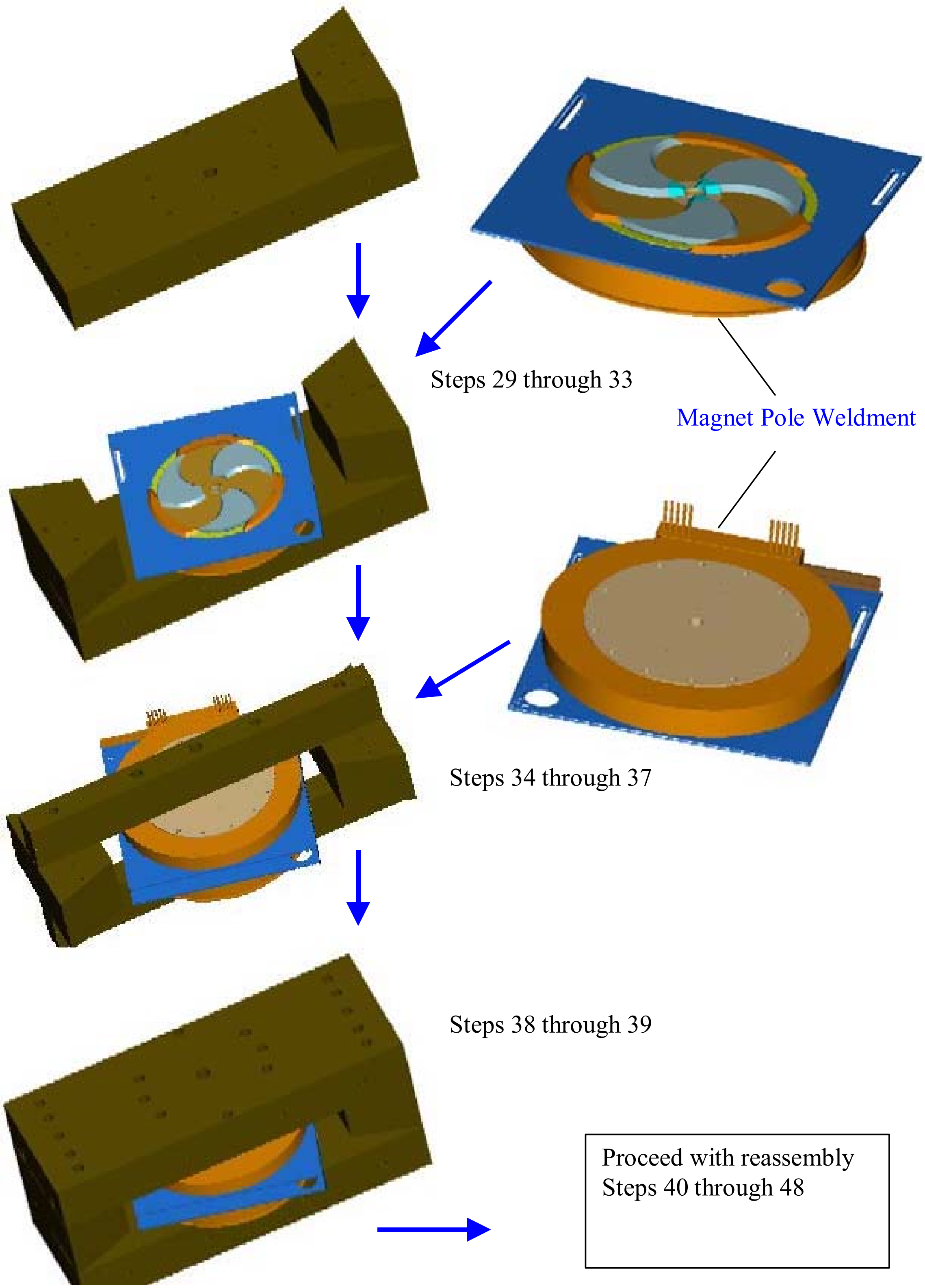

Figure 6.3 Reassembly process for the iron yoke

Chapter 7

Decontamination

This section is based on discussions with the EH&S Radiation technician, Robert Fairchild.

All materials used in an accelerator are classified as volume contaminated. Consequently, all materials removed from an accelerator are considered to have some radioactivity, regardless of the actual radiation readings. Therefore, scrap material from the accelerator cannot be recycled as standard scrap metal would be.

Procedures have been developed at the 88-Inch Cyclotron for accelerator maintenance and the upgrade planning would build on this experience:

Cleaning of large internal components such as the resonator tanks and the Dee vacuum tank can be done with a vacuum cleaner, and water and detergent scrub. No respirator protection is required. This is similar to the process used on the deflector regular maintenance (See Fig. 7-1 below).

Figure 7.1 Decontamination process during standard deflector maintenance.

To facilitate the decontamination, a local radioactive measuring system will need to be set up to do sample assays. A high purity germanium detector already exists in Bldg 88, Rm 135 that can be utilized. A memorandum of understanding will also have to be drafted with the LBNL Technical Services Group, TSG (Contacts are Dave Rogers, Howard Shoop) stating that this is a TSG approved equipment.

During disassembly, airflow must be kept to a minimum. Roll-up doors to the High Bay must kept closed during the decontamination. Constant air sampling will have to be conducted. A radioactive storage area will be set up in High Bay in which contaminated items can be bagged and stored.

Items that could be problematic to decontaminate are the carbon absorber material used in the cryo-panels.

EH&S will be able to support one full-time RCT in the facility, but a second RCT will be necessary during the major disassembly, maybe about 3-4 months. Below are some rough estimates of the additional RCT time required for the decontamination effort of some of the major components. The remainder of the RCT time will be used for sampling and counting.

Table 7.1 Additional estimated decontamination manpower requirements

Activity	Duration
RF tank removal	80 man-hours
Deflector Removal	30 Man hours
Component Swipes and bagging	100 man-hours
Dee Stem and Dee removal	30 Man hours
Magnets, Poles and pole components	400 Man-hours
Total	**640 Man-hours**

Chapter 8

Seismic Retrofit

The cyclotron vault shielding block structure does not currently meet all the seismic requirements. For example, the tension rods, which tie the east and west corner roof blocks together are inadequate to resist the forces that would be generated in a major seismic event. In fact, a seismic retrofit of the vault shielding blocks has been under consideration (subject to budget).

In order to better understand the seismic concerns, a brief discussion was conducted with LBNL structural engineer, Fred Angliss. This discussion concluded that the facility roof, or walls could only collapse, if the wall blocks would move their full depth, about 10 feet. Subsequently, the blocks supported above would fall. It seems unlikely that these massive blocks would travel that far in a seismic event; however, even if the wall blocks did not move ten feet and collapse the vault, it is conceivable that the roof blocks along the east and west edge of the vault will fall as they "spall" off the vault.

However, if the upgrade would be classified as on-going construction and the shielding blocks are only partly removed, there may not be a requirement to improve seismic structures. This issue will have to be resolved during the upgrade-planning phase.

If the facility shielding blocks are completely dismantled, it will be required to seismically upgrade the shielding blocks to comply with chapter 23 of PUB-3000. It is unclear where funds for this seismic upgrade will be budgeted from, but it is typically the responsibility of the program using the facility that bears the costs. A facilities estimate was quoted at around $1,200,000 prior to adding escalation, burden and 20% contingency. Including the later items, the total costs for the seismic retrofit are estimated around $2 million dollars. These costs were rolled up in the total of the facilities quote of $3,673,610 to remove and retrofit the shielding blocks. It should be noted that is amount is conservative since it is based on previous seismic retrofit at B88 of the Cave areas.

Chapter 9

Schedule and Cost

9.1 Man-power requirements

A resource loading based on the upgrade schedule (see Fig 9.1) was used to determine the minimum staffing required to complete the upgrade. The upgrade will require a multi-disciplinary staff of at least 8 persons. The disciplines include mechanical technicians, machinists, cyclotron operator, electrical installer, electrical coordinator, radiation control technician, mechanical and electrical designers, Mechanical and Electrical Engineer and Physicist. The minimal staffing costs are given in Table 9.1 below. The minimum increment for resource loading was 1 FTE/day for technicians and 0.25 FTE /day for everyone else. The resource requirements were not load leveled and peaked during assembly and disassembly periods. The schedule was based on a staffing of 11 persons and could be accelerated with additional personnel. At this staffing level, not everyone was utilized 100% throughout the schedule period. Therefore, it would be necessary to supplement the staff with additional work. For example, engineering, physicist and designers were at 50% utilization and below for the majority of the time.

9.2 Schedule

The schedule shown below in Table 9.1 illustrates the stages of the upgrade. The total upgrade lasts about 24 months, but there are several items that could significantly shorten this time. The critical path is the removal of the shielding blocks, which cannot begin until the VENUS and AECR along with the other injection systems are removed from the roof. The time allocated for both the removal and installation are 6 months each. Any reduction in this process would reduce the schedule proportionately.

Other long lead items on the schedule are the fabrication of the vacuum plates which is 3 months and the machining and welding of the poles which is about 1 ½ months. It is possible to machine the vacuum plates in parallel and this is incorporated in the schedule.

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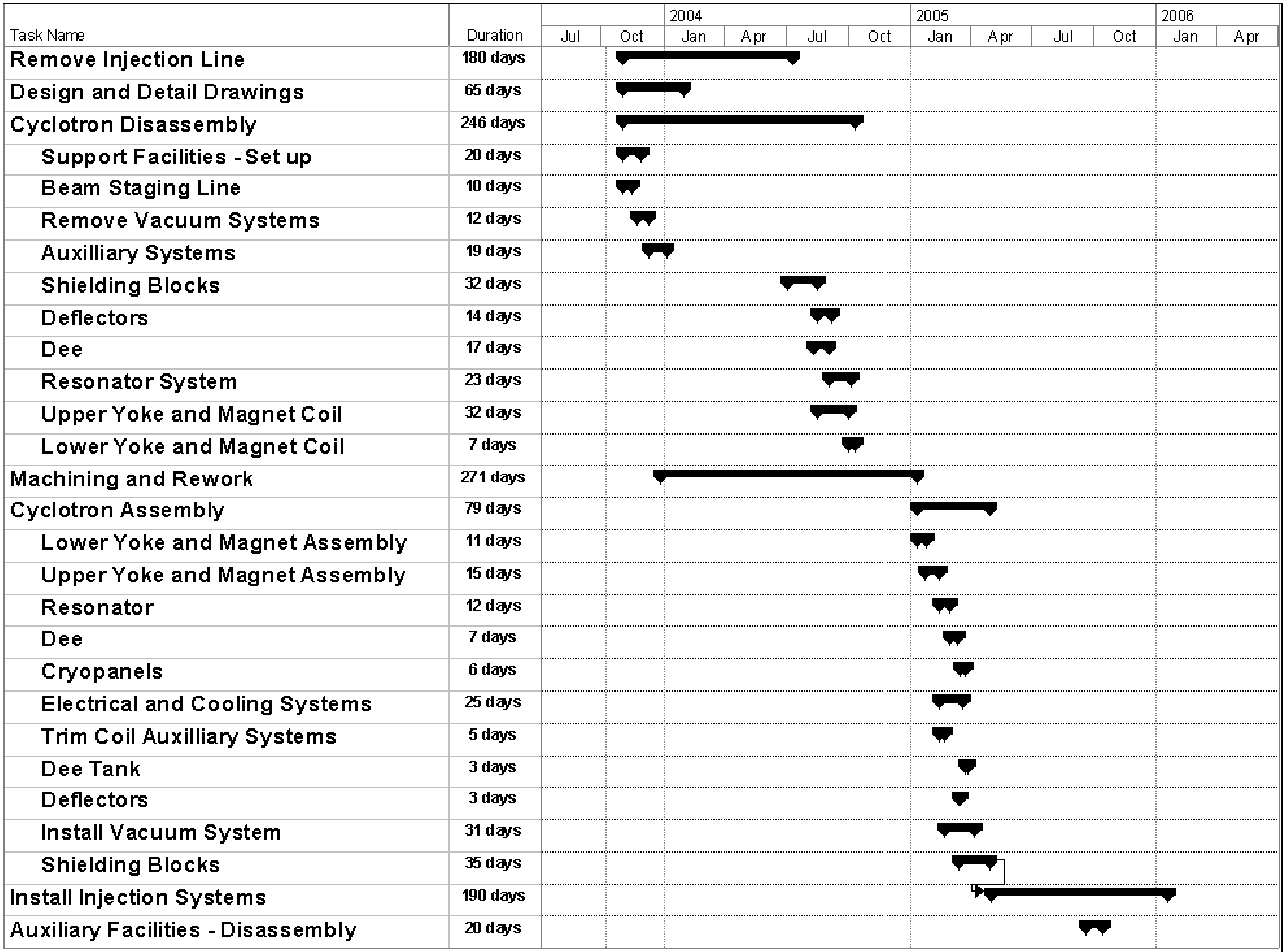

Figure 1 Fiscal Year '04, '05 and '06. Level 1 Schedule

9.3 Cost Estimates

The basis for the cost estimates contains the minimum manpower, materials and fabrication. The facilities' cost estimate (section 9.4) is rolled up in Table 9.2. The total project costs are $7,936,346. The spreadsheet for the calculations is included in the appendix.

Table 9.1 Total Upgrade Costs per Fiscal Year includes 20% contingency

Item	FY04	FY05	FY06	Project Total
Facility Manpower	$1,546,500	$1,347,600	$410,400	$3,304,500
Riggers and Facility	$950,000	$573,220	$200,390	$1,723,610
Welded Tank	$179,736	$0	$0	$179,736
Trim Coil Cooling Manifold Repair	$35,400	$0	$0	$35,400
Vacuum System Upgrade	$722,700	$0	$0	$722,700
Bolt Preloader	$20,400	$0	$0	$20,400
Sub Total	**$3,454,736**	**$1,920,820**	**$610,790**	**$5,986,346**
Optional Items				
Trim Coil Tray Vacuum Upgrade	$200,000	$0	$0	$200,000
Facility Retrofit				
Seismic Retrofit	$0	$1,950,000	$0	$1,950,000
Total	$3,654,736	$3,870,820	$610,790	**$7,936,346**

9.4 Facilities Cost Estimates Summary

LBNL Facilities department will be handling the major lifting and utilities associated with disassembly and reassembly. This includes the injectors, electronic racks, magnets, shielding blocks, utilities and the cyclotron itself. A cost estimate[i] was provided by Facilities and is summarized here in Table 2. A full copy of the estimate can be found in Appendix XX. The final costs of $3,673,610 and is calculated for the 2-year project as fully burdened with G&A, 20% contingency and seismic stabilization (upgrade) of the shielding blocks. A substantial amount of the quote is comprised of the $631,892 in contingency and $1,184,085 (pre-burden) for seismic stabilization and without these two items the costs for removing the shielding blocks is less than $2.0 million.($1,950,000 including burden, contingency and escalation)

Another big ticket item for the amount of $201,802 unburdend is item #2.6 shown in Table 2 below which is placing steel plates on the parking lot parking lot surface to support the shielding blocks during storage. The cost of the steel plates is $181,800. Only a small portion of this cost could be partially offset by reselling the steel after it is used (as long as the steel plates can be considered non-contaminated after contact with the shielding blocks), but this would not be only pennies on the dollar.

Table 9.2 Summary of Facilities Department Costs for Cyclotron Upgrade.

Fully Burdened, Reference W.O. No WG1450 dated 5/28/03

Description	**Labor**	**Material / Equipment.**	**Sub-Contract**	**Total**
Total Crafts Work Order Direct Cost before burden, without Item # 5.50 Seismic Stabilization Item #2.60 General Site work – Shielding block storage area	$668,147	$77,903	$178,033	$933,253
Item #2.60 General Site work – Shielding block storage area	$10,832	$181,800	$9,170	$201,802
Item # 5.50 Seismic Stabilization	$862,785	$321,300	0	$1,184,085
Total Crafts Work Order cost before burdens	$1,505,040	$537,059	$187,204	$2,229,303
Total Burden 3.5% Procurement & 45% G&A	0	0	0	$703,017
Escalation 4.4%	0	0	0	$129,022
Contingency 20%	0	0	0	$612,268
Total Estimated Costs				$3,673,610

[i] LBNL, Facilities Crafts Work Order No WG1450. Released 3/31/03. The total estimate was 3.66 million dollars that included seismic upgrades and a 20% contingency.

Appendix I

CYCLOTRON VACUUM TESTING 22 March 1996

MAIN MAGNET YOKE DEFLECTION v: MAGNET CURRENT

This measurement was intended to re-establish how much the main magnet yoke deflected as the main magnet was powered-up. A dial indicator was used to measure changes in the magnet yoke spacing with magnet currents in the range of 0 to 2400 amps.

The dial indicator was clamped to an aluminum stand resting on the lower magnet yoke. The dial indicator and stand were arranged vertically, and almost in contact with the Cyclotron south port window ring, and centered on the window. As magnet current increased, the attractive forces between the pole faces pulled the yoke pieces toward each other, compressing the dial indicator.

Main magnet current was raised in 100A increments through the range of 1000 to 2400 amps, then returned to 0A, while vertical deflection measurements, in inches, were taken from the dial indicator. All tests were run with vacuum in the low 10E-06T range: pressure pulsing (believed to be a periodic leak in the lower main magnet seal) was occuring throughout the measurements: pulsing amplitudes and approximate period are listed below.

Time	Current	Gap change	Pres base	Pulse ampl	Period	Comment
≈1053	900A		1.6E-06			large pressure rise.
1100	1000A	start	3.0E-06	0.2E-06	80s	pulse period decreases as pressure rises
1114	1000A	0.0000"	3.0E-06	0.2E-06	72s	slow pressure rise
1115	1100A	-0.0003"	<2E-06	0.05E-06	70s	rapid pressure drop to <1.9E-06. Gap relaxed back to -0.0001"
1125	1200A	-0.0004"	<1.6E-06	0.05E-06	100s	Gap relaxed back to -0.0003"
1134	1300A	-0.0007"	1.4E-06	0.05E-06	102s	Gap stable
1140	1400A	-0.0008"		0.05E-06	130s	
1144	1500A	-0.0010"		0.05E-06	135s	
1146	1600A	-0.0013"	1.4E-06	0.2E-06	60s	pulsing ampl increased
1147	1700A	-0.0016"	1.4E-06	0.2E-06	55s	
1149	1800A	-0.0019"	1.4E-06	0.2E-06	50s	
1152	1900A	-0.0021"	1.4e-06+	0.2E-06+	55s	
1154	2000A	-0.0029"	1.45E-06	0.25E-06	55s	
1156	2100A	-0.0032"	1.5E-06	0.25E-06	55s	
1158	2200A	-0.0036"	1.55E-06	0.25E-06	55s	
1200N	2300A	-0.0039"	1.55E-06	0.25E-06	55s	
1202	2400A	-0.0042"	1.55E-06	0.25E-06	55s	
1212	0000A	+0.0038	>6E-06			Run to zero current

Dennis Collins
Dave Clark

Manufacture & Procurement Costs

System	Item No	Description	Capacity	Vendor	Qty	Unit Cost	Discount	Total Cost	Comments
I. Vacuum System									
	1	Cryo Pump CyroTorr 10 3000 l/s air	3000 l/s air	HELIX	6	$10,000	10%	$54,000	5 + 1 spare
	2	Cryo Compressor CTI-9600		HELIX	5	$10,000	10%	$45,000	
	3	DP 35 inch Gate Valve rebuild		Out Sourced	2	$4,000	10%	$7,200	
	4	Cryo Pump Gate valve	10 inch	MKS	5	$7,500	10%	$33,750	
	5	Cryo Controllers			2	$2,000		$4,000	
	6	Turbo Pumps	2100 l/s	Pfeiffer	5	$40,000	10%	$180,000	
	7	Controllers		Pfeiffer	5	$20,000	10%	$90,000	
	8	Mechanical Pumps - Turbo	80CFM	Evert	5	$10,000		$50,000	
	9	Turbo Pump Gate Valve	10 inch		3	$15,000		$45,000	
	10	Piping	8 inch		6	$3,000		$18,000	
	11	Cryo Pump Manifold and Flanges	10	Out Sourced	2	$10,000		$20,000	
	12	UHV Gauge and Controller			6	$850		$5,100	
	13	Compressor helium Flex lines	3/4 inch x 20 ft	Helix	10	$880		$8,800	
	14	Mechanical Pumps - Cryos	80CFM	Evert	2	$10,000		$20,000	
	15	Misc Hardware and Gaskets			2	$1,000		$2,000	
	16	Roughing Vacuum Lines	6 inch SS tube	Out Sourced	200	$25		$5,000	
	17	Roughing Vacuum Flanges and Gaskets	6 inch, etc		24	$600		$14,400	
	18	Contingency					20%	$120,450	
		Vacuum System Subtotal						$722,700	
II. Vacuum Tank	19	Vacuum Tank 304L SS Top and Bottom	Material	Out Sourced	2	$5,000	10%	$9,000	3300 lbs * $1.50/lb
	20	Vacuum Tank 304L SS Sides	Material	Out Sourced	4	$1,050	10%	$3,780	700 lbs * $1.50/lb
	21	Vacuum Tank 304L SS Top and Bottom	Machining	Out Sourced	1	$20,000		$20,000	
	22	Vacuum Tank 304L SS Sides	Machining	Out Sourced	1	$20,000		$20,000	
	23	Poles Upper	Rework	LLNL, LBNL?	1	$22,500		$22,500	Activated requires special handling
	24	Poles Lower	Rework	LLNL, LBNL?	1	$15,000		$15,000	
	25	Welding Tank	Welding	LLNL,LBNL?	1	$17,000		$17,000	
	26	Welding Poles to Tank	Welding	LLNL, LBNL?	1	$30,500		$30,500	
	27	Inspection	Inspection		1	$12,000		$12,000	
	29	Contingency					20%	$29,956	
		Vacuum Tank Subtotal						$179,736	
III. Trim Coil	30	Repair Trim coil Tray		LBNL	1	$29,500	0%	$29,500	
	31	Contingency					20%	$5,900	
		Trim Coil Subtotal						$35,400	
IV. Bolt PreLoader	32	Drwg no.		LBNL	1	$17,000	0%	$17,000	
	33	Contingency					20%	$3,400	
		Misc Subtotal						$20,400	

88 Cyclotron		**Contacts:**		Daniela Leitner x7814		
				Steve Abbott x7738		
Document includes	127 ProE drawings					
Major Subassembly	**Subassembly**	**Cat. Code**	**Dwg. No.**	**2nd Line Title**	**3rd Line Title**	**Comments**
Steel	Yoke	8801-26	9B2616M	Magnet Core	Assembly	Includes details of N & S Legs /w bolts
	Poles	8801-28	9B2626J	Magnet Core	AssemblyDetails	Includes details of Center Slug & Sleeve; gasket groove,
						magnet yoke bolt, magnet leg stud, dowel pin details
Magnet Pole Tips		8801-28	9B7456	Magnet Pole Tips	Assembly	major assembly of pole tips onto dee tank vacuum plates;
						includes midhills, valley floors, outer hills, and rose shims
	Midhill		9B5264-1		Midhill - Upper	
	Midhill		9B5264-2		Midhill - Lower	
	Outer Hill		9B6644-1		Outer Hill - Lower	
	Outer Hill		9B6644-2		Outer Hill - Upper	
			9B7424-1		Rose Shim - Lower	
			9B7424-2		Rose Shim - Upper	
	Inner Hill	8801-28	9B2326	Magnet Pole Tips	Inner Hill Assembly	assembly of upper & lower inner hills onto valley floors,
						including central plate
	Inner Hill		9C2093-1		Inner Hill - Upper	
	Inner Hill		9C2093-2		Inner Hill - Lower	
			9C2104		Central Plate	
			9B5274-1		Valley Floor - Lower	
			9B5274-2		Valley Floor - Upper	
			9B5254		Midhill, Drill & Machining Jig	
Dee Tank		8801-07	9B4535-1	Dee Tank	Dee Tank Main Plate - Upper	
			9B4535-2	Dee Tank	Dee Tank Main Plate - Lower	
			9B5356	Dee Tank	North Cover Plate	
			9B5366	Dee Tank	East Cover Plate	
			9B5376	Dee Tank	South Cover Plate	
	Outer Hill Install		9B6834		Outer Hill Installation	for installing outer hills relative to midhills
Dee		8801-04	9D4546	Dee	Assembly	
			15C6576	Dee II	Asembly	
Main Coil		8801-27	9B4515	Magnet Main Coil	Assembly	
			9B4525		Assembly Cross Section	shows conductor cross section
			9B4644		Curved Plate #1 & #4	
Trim Coils	Main Assembly	8801-30	9C2896	Magnet Trimming Coils	Assembly	All assemblies are broken down to upper and lower assys
			9B8115		Base Asssembly	
			9B7726		Valley Coil Assembly	
			9B7736		Valley Coil Lead Assembly	
			9C2396		Circular Coil Assembly	
			9C3393		Valley Coil Base Plate Spacer	
Center Region		8801-03	16M0925	Center Region	Center Region Asembly - External Source	
			15D5983		Dummy Dee - Insert - Holder	
			15D5992		Dummy Dee - Insert - Holder Contact	
			15D6002		Dummy Dee - Insert - Holder Spring	
			15D5964		Dee Insert Tray (External)	
			15D9391		Dee Insert Shim	

			22C8244		Small Gap Dummy Dee Insert For External Source	
			22C8254		Small Gap Dee Insert For External Source	
	Dummy Dee		15D5976	Center Region	Dummy Dee	
Axial Injection	Glaser Lens #3	8001-02	18M7895	Axial Injection	Glaser Lens #3 Area Assembly	
			18M8023		8" Plug Upper Shield Tube	
			18M7934		8" Plug Slug	
			9B2626		8" Plug Sleeve	
			15C3542		8" Plu Spacer	
			18M8036		8" Plug Cover	
			15D2366		8" Dia Plug - Upper	
			18M8016		#3 Glaser Lens Core	
			18M8056		#3 Glaser Lens Coil	
	Inflector IV	8001-02	25C0694	Axial Injector	Inflector IV Assembly	
			25C0624		Inflector IV Shaft	
			25C0633		Inflector IV Grid Assembly	
			25C0642		Inflector IV Housing	
			25C0721		Inflector IV Mirror Assembly	
			25C0681		Inflector IV Base	
			25C0741		Inflector IV Feedthrough Cap	
	Iron Plug	8801-03				
	Two Inserts	8801-03				
	Reflector Pumps	8801-03				
Vacuum Chamber		8801-68/69				
RF Cavity		8801-54				
(5-16 mhz)						
Vacuum Pumping	Diffusion Pumps	8801-70				
	Two Cyro Pumps					
	Two Cryo Panels		22C6416	Cryogenic Pump Sys	LN & He Unit Space LO	shows placement of cryo panels within the vac chamber
			16M8946	Cryogenic Pump Sys	Panel Assembly	first panel designed by don morris
			16M8616	Cryogenic Pump Sys	Cryo-Panel Frame	
			22C6404	Cryogenic Pump Sys	LN Panel Assembly	second panel designed by Loren Stolit
			22C6396	Cryogenic Pump Sys	LN Panel Solder Assembly	
Deflector II		8801-12	10P8375	Deflector II	Assembly	
			10P8045	Deflector II	Main Plate	
			10P8385	Deflector II	Cover Plate	
			10P8444	Deflector II	Main Plate Bolting Angle	
			10P4834	Deflector II	High Voltage Entrance Electrode	
			18M4104	Deflector II - SeptumIV	Assembly	
			10P4886	Deflector - Mark II	HV Middle Electrode	
			10P4876	Deflector II	Ground Middle electrode	
			10P4804	Deflector II	Mark II H.V. Electrode	
			10P4824	Deflector II	Ground Exit Electrode	
(10-100 kilovolts)						
Resonator Tank		8801-48	9B5165	Resonator Tank	Detail	machining and welding detail drawing
			9C5556	Resonator Tank	Copper Liner Installation	